CHAPTER IV

GUIDANCE AND CONTROL

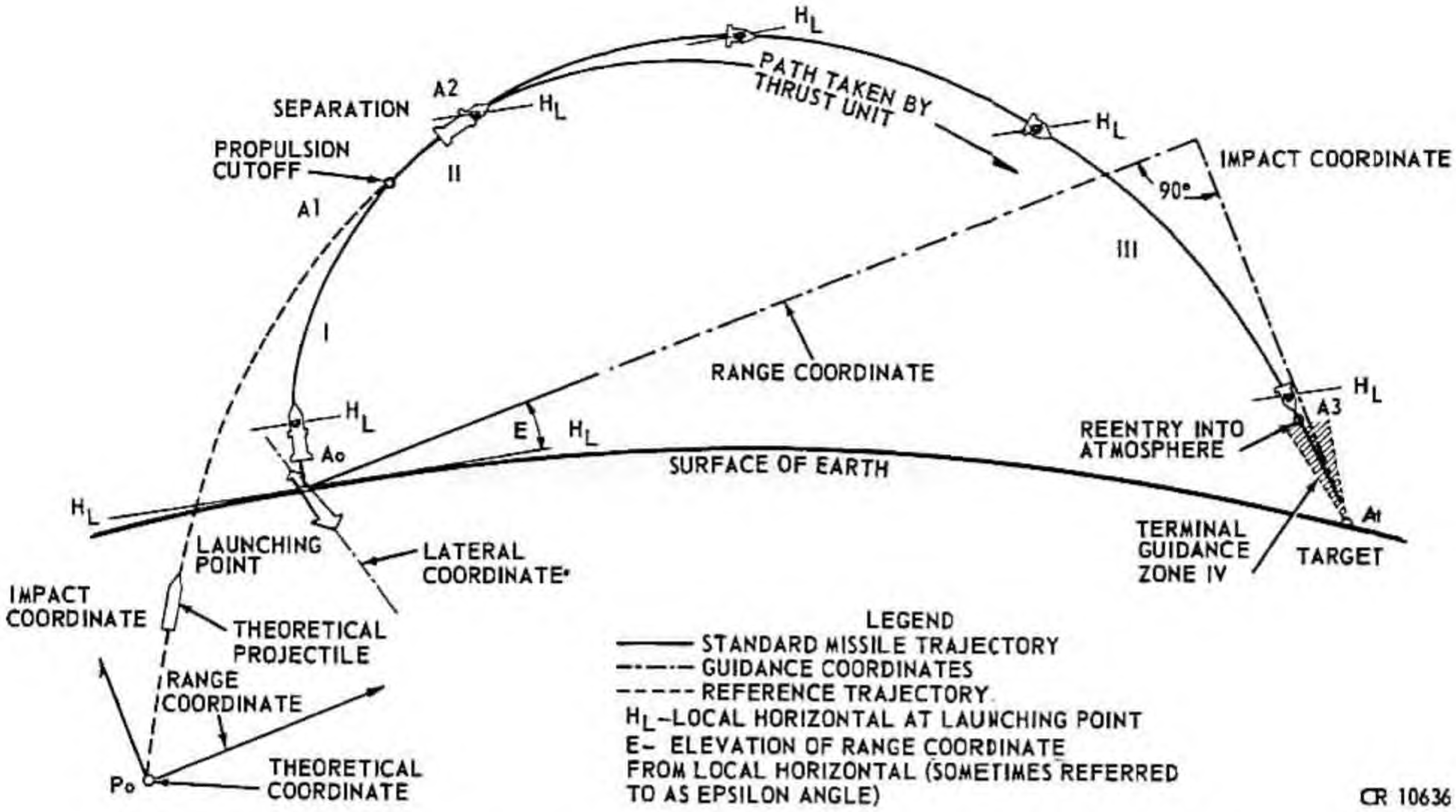


Figure IV-1 – Standard Trajectory and Reference Coordinates

CHAPTER IV

GUIDANCE AND CONTROL

GENERAL

The REDSTONE Missile system employs three trajectories in order to place the warhead on target. The first trajectory to be considered is known as the reference trajectory. This is a pure ballistic trajectory drawn from the target back to a point of launch. The problem then arises that in order to fire the missile from this point and to have it follow a pure ballistic trajectory, two conditions must exist: 1) the missile would have to be fired from an angle other than vertical, and 2) the missile would have to have its cutoff velocity at point of launch. Since neither of these conditions can be met, a practical solution must be found. The solution is to move the launching point closer to the target. The missile may then be fired from a vertical position and programed or tilted into the reference trajectory. If the missile velocity, as the missile enters the reference trajectory, is the same as that of the theoretical missile velocity at that point, the end result will be the same; both missiles would strike the target. This second trajectory is known as the standard trajectory and is the one that is used.

The third trajectory is the actual trajectory: the one the missile follows, including all deviations and corrections. The perfect flight would be one in which the standard and actual trajectories coincided at all points. This perfect flight, however, would never occur because of variations in drag, thrust, winds, and other influencing factors. The function of the guidance and control system is to make the actual and standard trajectories coincide at impact.

The standard trajectory is divided into four phases of flight. Phase I is the portion of flight that extends from launch to cutoff. From launch the missile rises vertically and is then tilted to intercept the reference trajectory. During the first portion of Phase I, the missile is controlled by four carbon vanes located within the jet blast. When the missile has reached a velocity sufficient for it to become aerodynamically stable, four air rudders located at equidistant points around the outside of the tail section take over the control function. The transition of control from carbon vanes to air rudders, however, is gradual because both the vanes and the rudders are driven by the same actuator and both turn simultaneously. At cutoff, the missile will be out of the earth's atmosphere and will have sufficient velocity to carry it to the target. Cutoff will occur between 96 and 107 seconds after launch, depending upon the range. Phase II begins with engine cutoff and ends with the separation of the body unit from the thrust unit; missile separation occurs at 127 seconds after launch.

Phase III begins at separation and ends at a point called "Q" (the point at which the missile re-enters the earth's atmosphere). This portion of flight takes place outside of the earth's atmosphere and is therefore known as spatial flight. During spatial flight, missile control must be accomplished by an action-reaction type device, since any aerodynamic device would be useless because of the lack of lift. These control devices are air jets which are located around the circumference of the skirt section. Phase IV is from "Q" to impact and is generally referred to as the "dive phase".

The REDSTONE, like any other missile, has six degrees of freedom: three angular and three translatory. The missile is free to pitch and yaw about its center of gravity and to roll about its longitudinal axis. It is also free to be displaced to the right and left, up and down, or backwards and forwards. The three angular movements deal with the missile's attitude and are, therefore, control functions; the three translatory movements deal with the missile's physical displacement and, therefore, are guidance functions. This is the distinction between guidance and control. The REDSTONE guidance and control system is capable of measuring any deviation in attitude or any displacement from the standard trajectory. This is accomplished by the use of a stabilized platform known as the ST-80. The ST-80 provides the missile with a space-fixed frame of reference. The platform is stabilized at the launching site and will maintain a reference, throughout flight, space-fixed to the local horizontal at the time of launch. By placing potentiometers between the stable platform and the missile's airframe, a means is provided for detecting and measuring the angular rotation of the missile about this reference. By using three potentiometers, errors in the pitch, roll, and yaw planes are detected and measured. These error signals carry the designation of ϕ (phi) signals and are classed as attitude error signals. With proper amplification and distribution to the various control devices, these signals are used to control the missile attitude during flight. A means is provided whereby the reference point of the pitch control potentiometer or command potentiometer may be changed during flight to cause the missile to pitch over and follow a ballistic trajectory. This is done through the use of a Program Device that feeds a continuous series of pulses to the stabilization system, causing the zero position of the pitch command potentiometer to shift. The missile control system will recognize this shifting zero point as an attitude error signal and will cause the missile to tilt over until the wiper on the potentiometer is aligned to the new zero. This process is known as pitch programing and is the means by which the missile is made to enter a ballistic trajectory and to maintain correct pitch attitude throughout flight.

In order to sense its physical position in relation to the standard trajectory, the REDSTONE Missile carries two gyro accelerometers: one for lateral measurements and one for range measurements. The lateral accelerometer measures accelerations to the right or to the left of the trajectory, and the range accelerometer measures the acceleration along the range coordinate. By first integration of these accelerometer signals, velocity information is obtained; second integration provides displacement information. First integration takes place within the accelerometer unit itself. The accelerometers are mounted on the ST-80 because this is the only component within the missile that does not change its orientation during flight. The sensitive axes of both

accelerometers must be aligned along their measuring coordinates. The lateral coordinate is crosswise to the trajectory plane. The range coordinate is formed by drawing a line from the point of launch to intersect at an angle of 90 degrees, a line drawn tangent to the trajectory at point of impact. The angle formed by the range coordinate and the local horizontal is the epsilon (ϵ) angle and varies from 20 to 43 degrees. The range accelerometer is aligned to this angle prior to launch.

As shown in the guidance and control block diagram (Figure IV-2), the REDSTONE guidance and control system is made up of five basic subsystems: Stabilization, guidance, control, program, and power.

The stabilization system is composed of the ST-80, the alignment amplifier box, and the servo-loop amplifier box. These three units provide the missile with a space-fixed reference.

The guidance system contains the lateral and range computers. The two computers, in conjunction with their respective accelerometers located on the ST-80, provide the missile position with reference to the standard trajectory.

The program system contains the program device and the missile step switch and provides a time base for the missile.

The power system is composed of an 1800 VA inverter, two 28-volt self activating d-c batteries, and one 60-volt d-c power supply. The 1800 VA inverter provides 400-cps, 3-phase, 115-volt output for missile components that require highly regulated power, such as the program device. One 28-volt battery is utilized to drive the inverter; the other battery is used for general networks. The 60-volt d-c power supply is utilized for all command circuits, such as the command potentiometers.

The REDSTONE control system utilizes a control computer, a relay box, four actuators on the thrust unit, four actuators on the body unit, and four sets of spatial gaseous nitrogen jets, also located on the body unit.

Attitude control is maintained at all times. Lateral guidance is active during Phases I and IV. Range guidance is active only during Phase IV, but it computes engine cutoff during Phase I. Programing is maintained throughout flight in order to assure proper missile attitude. The control computer accepts these signals and mixes them in proper proportion for distribution to the various control surfaces. These units are interconnected as shown on the block diagram in Figure IV-2.

PROGRAM DEVICE

The program device is a three-channel magnetic tape recorder that uses 16-millimeter, 450-second Mylar tape. The information is recorded on the tape in the form of 2-kc pulses of 50-millisecond duration. Channel I provides the pulses for pitch programing which determine the missile trajectory. Channel II contains the pulses for the missile step switch, which is used for timing the flight sequence. Channel II also contains the dive program, which is activated at "Q", and is used for terminal guidance. Channel III is used for telemetry.

Tape motion is provided by a 115-volt, 400-cps, 3-phase motor which is coupled to 16-millimeter sockets through a mechanical differential. The tape is held under tension by a 28-volt d-c motor. This motor also compensates for the difference in speed as the tape moves from one reel to the other.

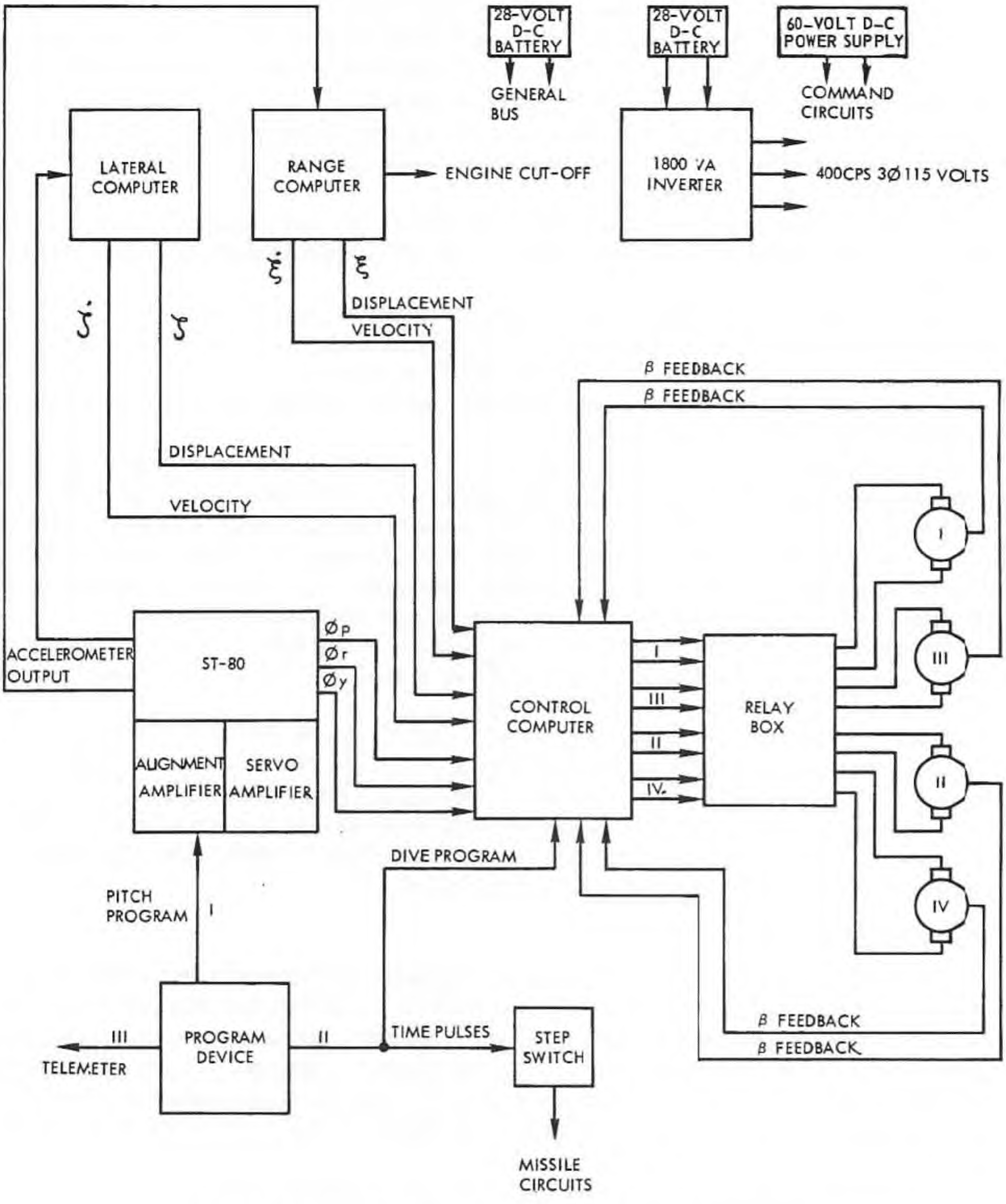


Figure IV-2 – Guidance and Control Block Diagram

The first time the program device is operated, a brake spring on the reel motor builds up tension which is released only upon a power failure. This increases reliability and prevents tape spillage during transit and operation. Transistor amplifiers, one for each channel, amplify the pulses from the tape and apply these pulses to output relays.

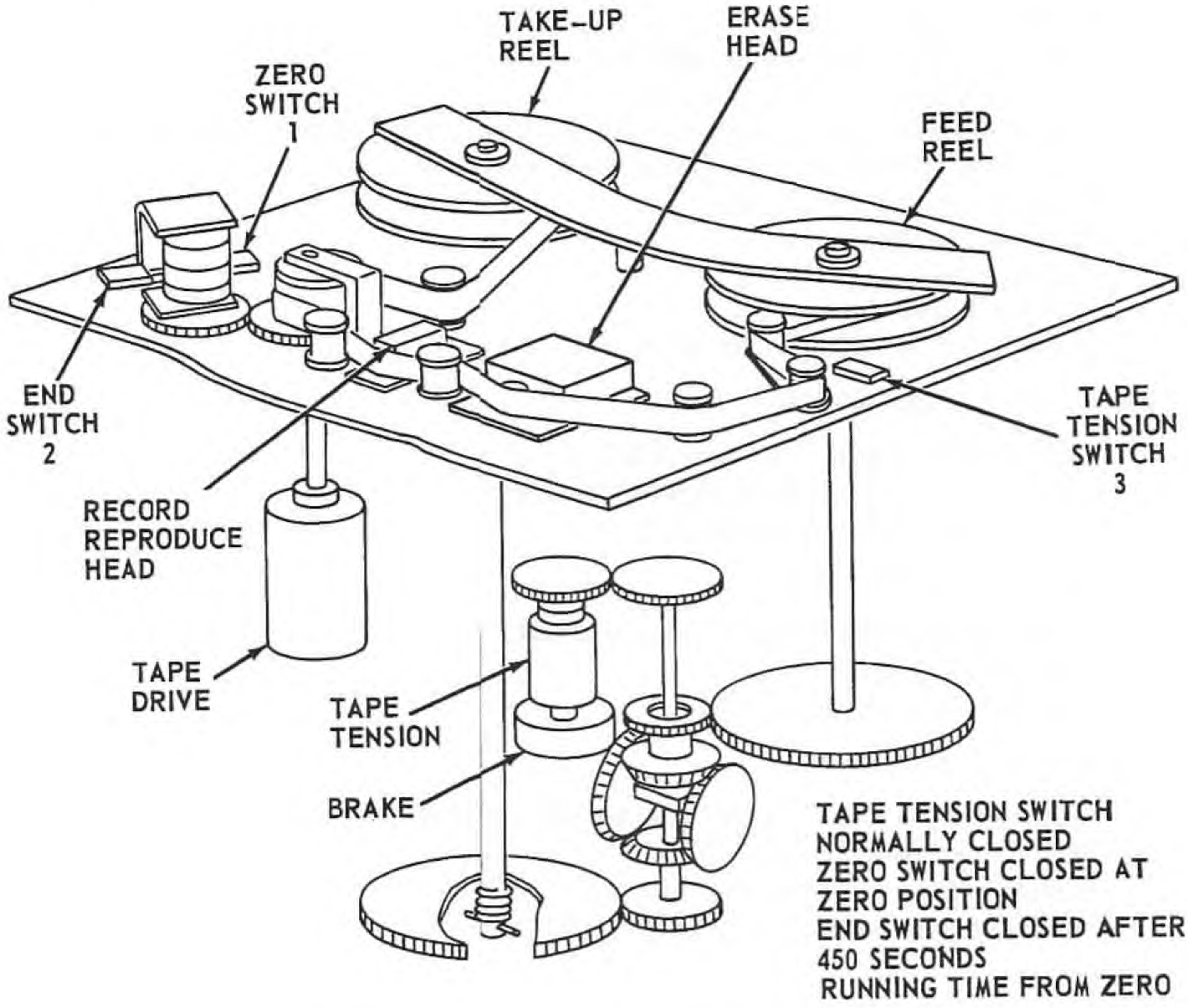


Figure IV-3 – REDSTONE 6700 Program Device

STABILIZATION SYSTEM

The accuracy of an inertially guided missile, such as the REDSTONE, is based primarily on the ability of the stabilization system to provide and maintain, throughout the flight, a space-fixed reference. Since the guidance and control error-sensing devices are mounted on this space-fixed reference, the need for stringent requirements to maintain this reference is obvious.

The stabilization system may be divided into four units: the ST-80 stabilized platform, the servo-loop amplifier box, the alignment amplifier box, and the stabilizer control panel. The following breakdown of each major component of the stabilization system indicates the location of minor components:

ST-80 Stabilized Platform

- 3 stabilizing gyros (x, y, and z), type AB-9.
- 3 servo motors (pitch, roll, and yaw).
- 2 air bearing pendulums (x and z).
- 2 integrating accelerometer assemblies (range and lateral), type AB-5.
- 3 command potentiometers (pitch, roll, and yaw).
- Program transmission unit.
- Internal gimballing.
- Caging assembly.
- Azimuth inductive pickup.
- Mainshaft – including centerpiece.

Servo-loop Amplifier Box

- 3 servo-loop amplifiers (stabilizing).
- 3 servo-loop amplifiers (accelerometers).
- Various relays and transformers.

Alignment Amplifier Box

- 3 torquer amplifiers (pitch, roll, and yaw).
- 2 pendulum bias circuits.
- 3 earth rotation bias circuits.

Stabilizer Control Panel

- Remote pendulum and earth-rotation bias adjustments.
- System energization circuits.
- System checkout meters and controls.
- Miscellaneous switches and indicators.

DESCRIPTION OF COMPONENTS

Stabilizing Gyros (x, y, and z gyros, type AB-9)

The rotor motor is a synchronous hysteresis type that uses the mass of the gyro rotor as the rotor of the motor. This motor rotates at 24,000 rpm and utilizes an air bearing about the precession axis of the gyro. An inner cylinder separated by air from the outer cylinder precesses with the gyro. Gyro precession is caused by the application of torque to the platform and gyro. An inductive pickup is used to provide an electrical output signal which denotes that the gyro has precessed in one direction or the other.

Accelerometers (range and lateral, type AB-5)

The rotor motor is a hysteresis synchronous type operating at 12,000 rpm. It utilizes an air bearing about the input, or sensitive, axis. An unbalanced weight or mass is mounted on the inner cylinder. When the platform experiences an acceleration or deceleration, the unbalanced mass applies a torque to the gyro and causes it to precess. A synchro transmitter attached to an output gear on the precession axis transmits the information to the guidance computers.

Servo Motors (pitch, roll, and yaw, 2-phase induction type)

Each of these motors has a fixed phase, while the other phase is provided from the outputs of the respective servo amplifiers. The motors apply torque between the stabilized portion of platform and the main shaft or missile.

Servo Amplifiers (pitch, roll, and yaw)

These amplifiers are practically identical. They receive a signal input from the inductive pickups of the stabilizing gyros, amplify it, provide the necessary phase shift, and feed the signal to the respective servo motors.

Air Bearing Pendulums (X and Z)

These pendulums are used to level the platform about the X and Z axes. The pendulums each use a slug which rides on an air bearing. When the platform is perfectly level, the slugs are positioned equidistant from either end of the pendulums, and the electrical output is zero. An off-level condition causes the slugs to move to one end or the other; the movement produces an electrical output, the phase of which denotes the direction in which the platform is off-level.

Azimuth Inductive Pickup

This pickup is used to determine when the stabilized portion of the platform (carrier ring) is perpendicular with respect to the mainshaft. It is a Dual-C type transformer, with a movable portion of the core (pole piece) attached to the carrier ring. When the platform is perpendicular to the mainshaft, the electrical output is zero. Being off the mechanical zero in either direction produces an electrical output with a phase indicative of the direction.

Command Potentiometers

Pitch, roll, and yaw potentiometers are used to provide the attitude signal voltages. These potentiometers are so attached on the platform that body and wiper move with respect to one another when the missile's attitude changes with respect to the stabilized platform.

Program Transmission Unit

This unit contains a program motor, a program solenoid, associated gearing, and a resolver. It is used to step the pitch potentiometer at a preset rate and preset distance to introduce a false error signal into the control computer. This unit receives from the program device the pulses necessary to operate the program solenoid. When the pitch command potentiometer is rotated, the rotor of the resolver rotates also. The resolver performs the interchange of signals from the roll and yaw gyro inductive pickups to the roll and yaw servo amplifiers as the missile pitches from vertical to horizontal and back to vertical.

Caging Assembly

This device is a motorized assembly which mechanically positions and locks or unlocks the carrier ring when power is to be removed from the stabilizer system, or after power is applied to the system.

Internal Gimbal

The internal gimbal is a system of gearing and bearings located partially on the carrier ring and partially in the mainshaft. This system provides freedom of motion of the platform in all axes.

Pendulum Bias Circuit

This circuit provides an electrical voltage to equal and cancel an output from the pendulum if the electrical and mechanical null are not in coincidence.

Torquer Amplifier

The X, Y, and Z amplifiers receive their input from the pendulums or azimuth inductive pickup, amplify it, and apply it to the torquer coils on their respective gyros.

Earth-Rotation Bias

While the platform is operating on the ground it is fixed to a point in space. As the earth rotates, there is a relative movement between the earth and the platform, thus causing the pendulums and inductive pickup to produce an output. The bias will torque the platform and cause it to precess at the earth's rate to keep it in coincidence, and to keep the outputs of pendulum and azimuth inductive pickup at zero.

FUNCTION OF THE STABILIZATION SYSTEM

The state of the art at the present time requires that the missile be mechanically attached to the platform through the gimbal system. Although the friction in the gimbal system is small, it is not negligible. Because of this friction, a torque is applied to the platform when the missile moves about its center of gravity or about its longitudinal axis. The stabilization system has the function of applying an equal and opposite torque to the platform to counteract the torque being applied by the missile movements, so that the platform does not deviate from its original setting. It is important to note that the stabilization system does not try to keep the missile from deviating in attitude. It merely keeps the platform from being dragged along with the missile. The relative movement between the missile and the stabilized platform is then measured electrically, and this output is called the phi signal.

The integrating accelerometers that are mounted on the platform are used to sense acceleration and deceleration along a particular coordinate. The range accelerometer senses acceleration and deceleration along the range coordinate, and the lateral accelerometer senses acceleration and deceleration perpendicular to the trajectory and in the horizontal plane. It is extremely important that these accelerometers do not change their measuring directions.

The ST-80 stabilized platform utilizes three air bearing powered gyroscopes. The principles of gyroscopic phenomena include that of rigidity and precession. The rules governing their action are:

Rigidity – a body rotating steadily about an axis will tend to resist changes in the direction of the axis.

Precession – that property of a spinning mass in which the plane of the spinning mass turns or tilts in the direction of applied torque.

A rotor of a typical gyroscope is shown in Figure IV-5. The arrow on the rim indicates the direction of rotation or spin. If a torque were applied to the gyro at any point on the shaft of the rotor, it would be effectively the same as if the torque were applied to a point on the rim in the same plane. The bottom half of the illustration shows torque effectively being applied to various points on the rim. If the rotor were spinning and point A′ were the point of effective torque, the rotor would not move in the plane of applied torque, but rather at a point 90 degrees away from A′ in the direction of rotation (point A″) and in the same direction of torque. This phenomenon is true only if the rotor is spinning.

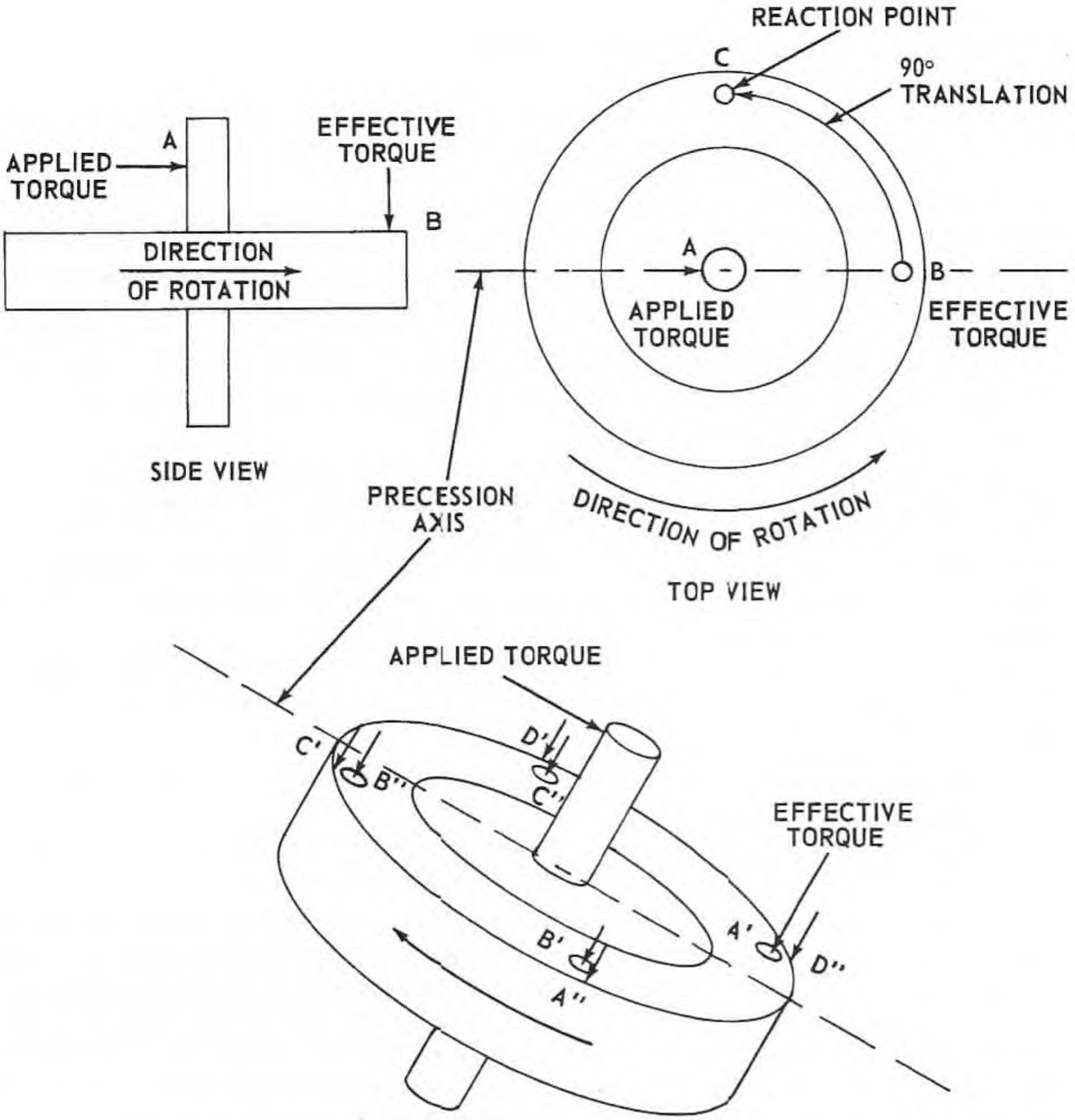


Figure IV-4 – Gyroscopic Spin and Precession

The air bearing principle relies on a steady flow of air to support or lubricate the bearing surface. The lightest oil available has enough viscosity to cause an erroneous output signal from the gyro inductive pickup. Figure IV-6 is an idealized drawing depicting the method used to separate one bearing surface from another by use of air flow. The use of air bearings on the precessional axis of the stabilizing gyros reduces errors to a minimum.

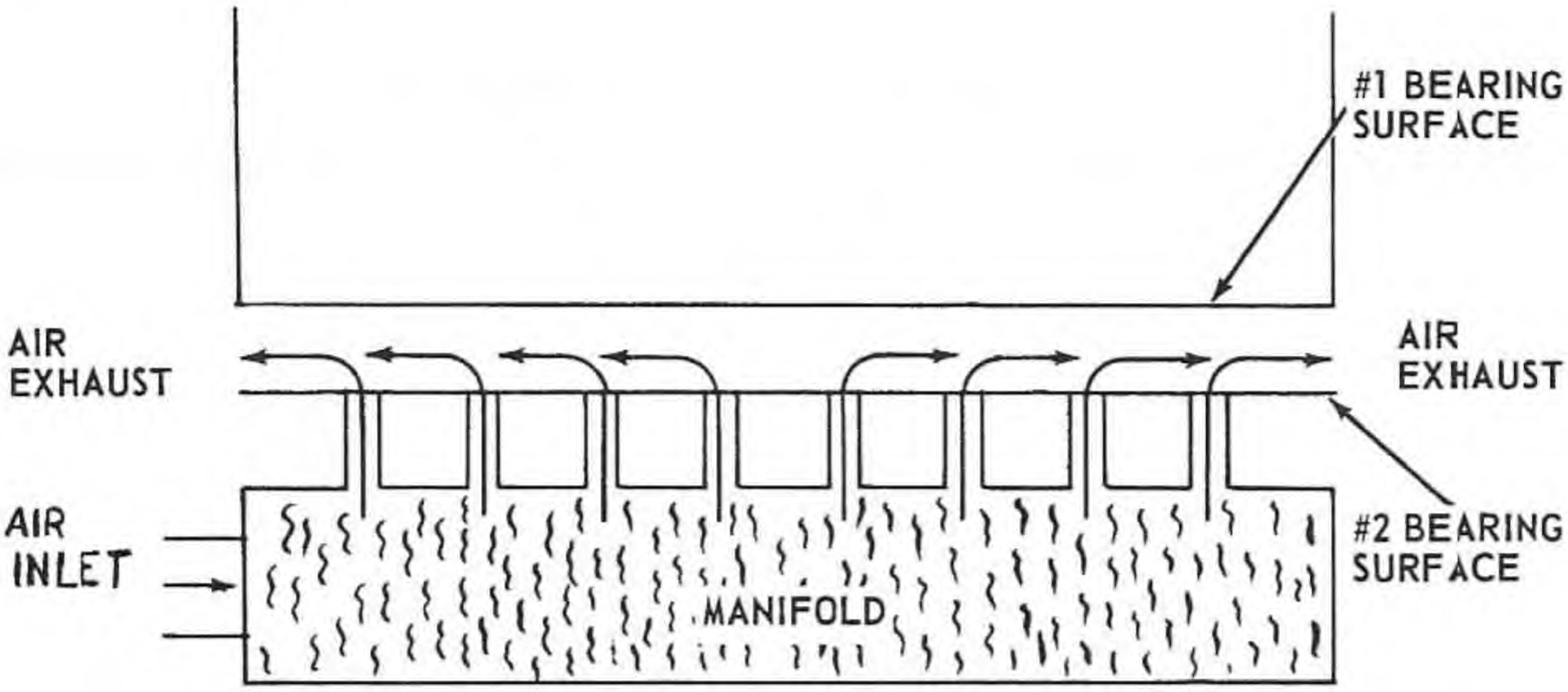


Figure IV-5 – Air Bearing Principle

The stabilization system's first problem is to level the ST-80 and to orient or aim it in the firing direction. This leveling and aiming is accomplished by means of the alignment circuitry and the stabilization circuitry. In leveling the platform to the local horizon, the x and z pendulums are used. Considering the pitch, or z axis, leveling, the z pendulum slug will be off level, thus an electrical output voltage with a phase indicative of the direction off level will be produced. This voltage will be fed into the torquer amplifier where it is amplified and fed back to the torquer coils mounted on the z stabilizing gyro. The torquer coils apply a torque to the gyro, which reacts by attempting to precess about an axis perpendicular to its normal precession axis. The platform responds by beginning to move in a direction of gyro precession. The gimbal friction then causes the gyro and inner cylinder to precess about the normal precession axis, and the inductive pickup is displaced. This produces an electrical output which is fed into the servo amplifier, where it is amplified and fed back to the pitch servo motor. The pitch servo motor drives against the pitch gear which is mounted effectively on the mainshaft. This removes the friction and allows the platform to rotate about the mainshaft until it has reached the point where the z pendulum becomes level and its output is reduced to zero. The same procedure is used for the leveling of the x pendulum.

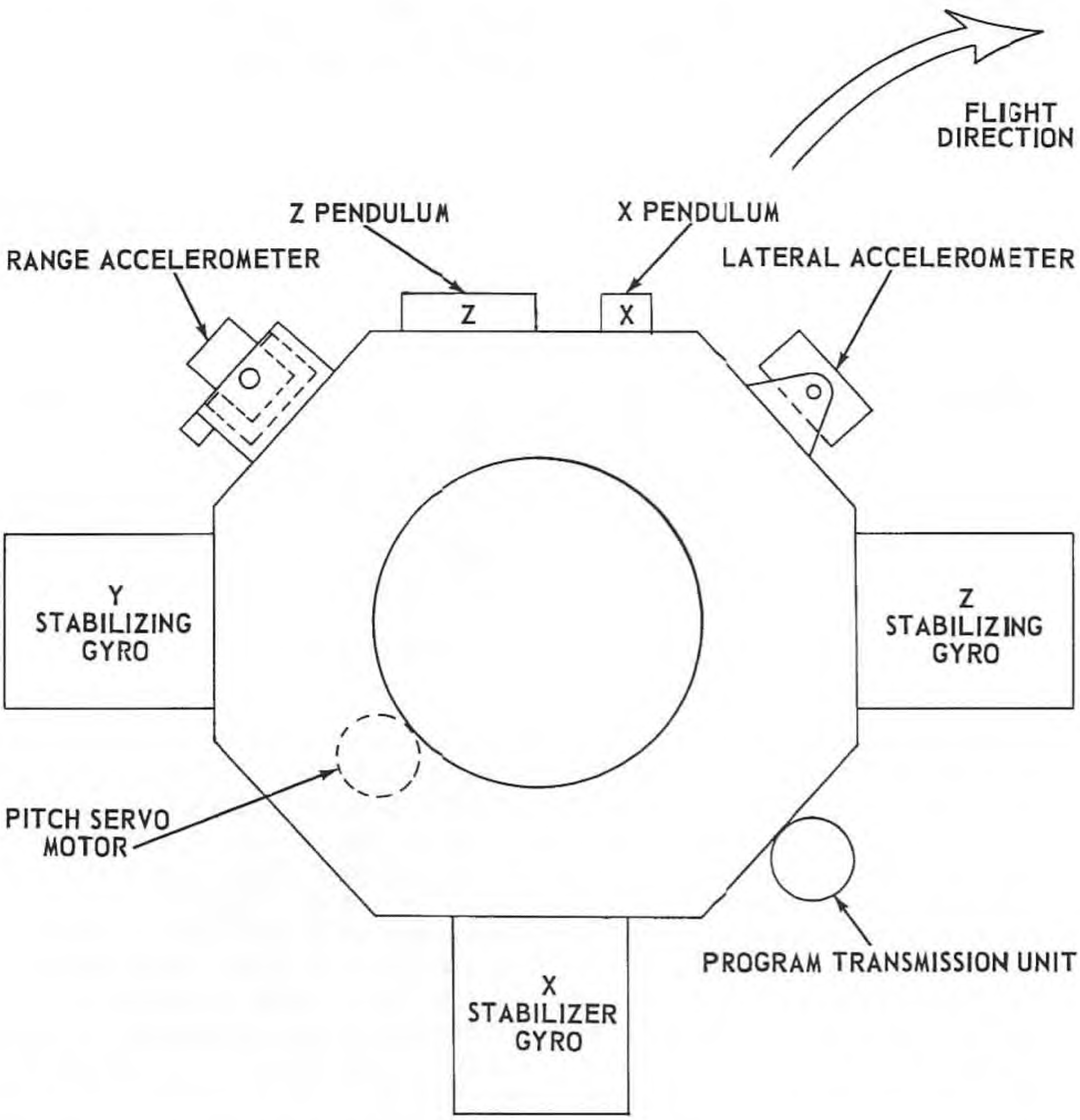


Figure IV-6 – Stability of the Platform Ring

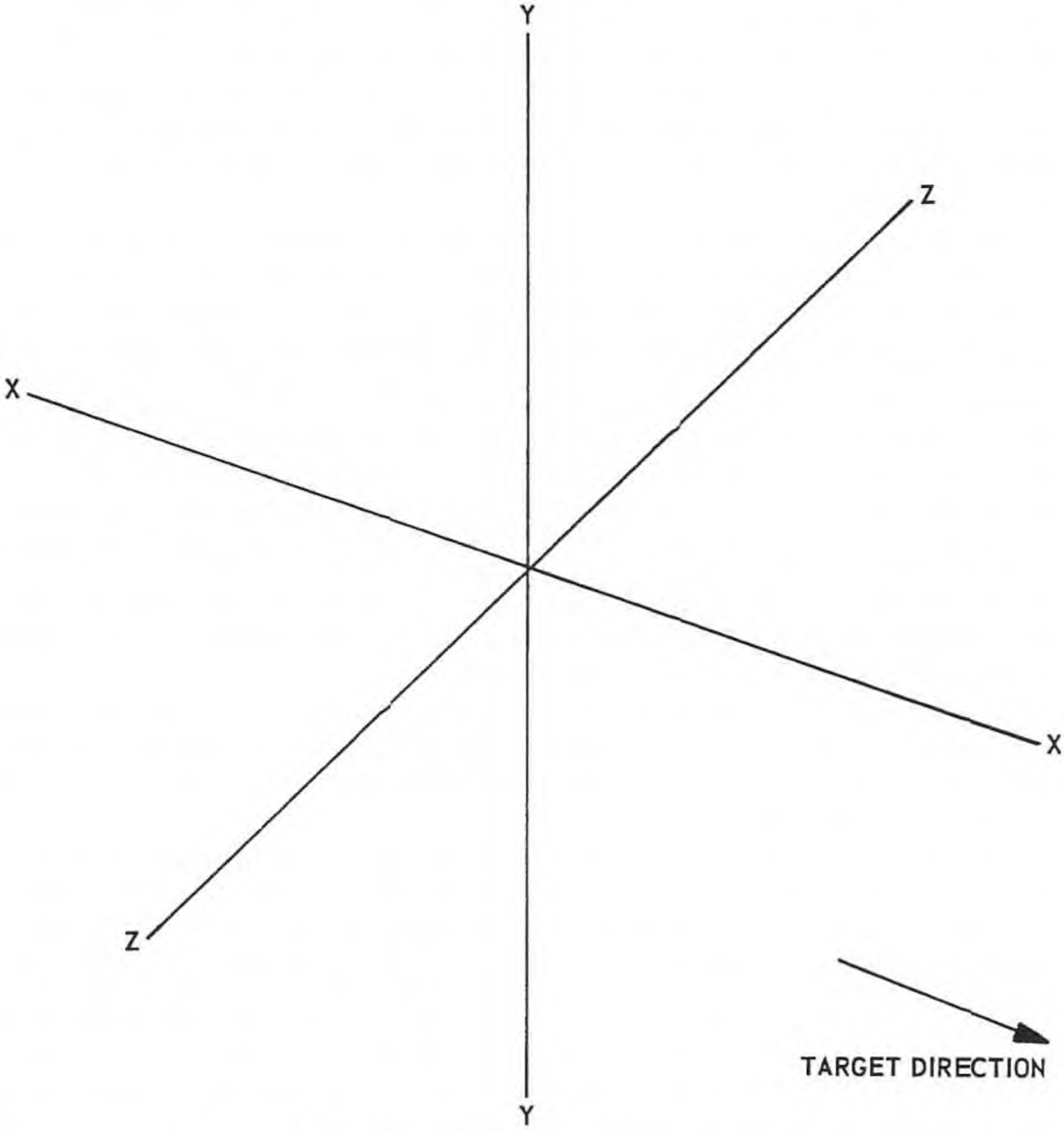


Figure IV-7 – Platform Coordinates

The azimuth inductive pickup senses when the mainshaft of the platform is not perpendicular to the carrier ring. The missile is oriented to the aiming azimuth by means of the porro prism and theodolite. The platform must then align itself to the missile or mainshaft. (The mainshaft of the ST-80 is attached to the missile.) The procedure is the same as that for the x and z channels with the exception of the sensing device, that is, the pendulum versus the azimuth inductive pickup.

In all three loops, the function is to continue to operate until the pendulums are level and the azimuth inductive pickup is nulled. These loops are then termed "null-seeking loops." However, due to the rotation of the earth, complications arise as long as the missile is on the launcher.

The platform is considered to be correctly aligned and oriented only when the pendulums and azimuth inductive pickup have zero output. Because of the rotation of the earth, the pendulums and azimuth inductive pickup will never really be zeroed out, for as soon as the servo motor stops turning, the rotation of the earth upsets the zero or nulled condition. Therefore, the platform could never be considered correctly aligned. Because of this situation, earth-rotation bias circuits have been incorporated into the alignment loops. Voltages are preset from the ground equipment and the value is predetermined and influenced by the geographic location of the firing site. This voltage causes the torquer coils to be constantly torquing the three gyros by an amount that will keep the platform perfectly leveled and oriented, thus keeping the pendulum and azimuth inductive pickup outputs at zero. This alignment circuitry will function until liftoff and will keep the platform earth-fixed. At liftoff the alignment circuits are de-activated; the platform then becomes space-fixed. The stabilization loops will then maintain the platform in its space-fixed position.

Basically, all three stabilization loops function identically. Roll and yaw, however, are modified by the use of a resolver to compensate for the interchange of the torquing planes of the two servo motors as the missile is pitched over from a vertical position to a horizontal position.

If a gust of wind causes a vertically rising missile to start pitching over, a torque is applied to the platform. Since a pitching motion is about the z axis of the platform, the z gyro will sense this torque because of gimbal friction about the Z axis. The reaction of the gyro would be to precess. As soon as the gyro moves the slightest distance, the inductive pickup will no longer be nulled, and consequently, an output voltage will be produced which will be of a particular phase indicative of the direction of the torque being applied to the platform. The output is fed to the servo amplifier, amplified, and fed back to the pitch servo motor. The pitch servo motor housing is mounted on the platform carrier ring, while the shaft and gearing drives a gear mounted on the mainshaft of the platform. Energizing the motor torques the gearing to cause the carrier ring to move in one direction or another about the mainshaft. The output of the servo amplifier causes the servo motor to apply a torque equal and opposite to that caused by missile movement. The rapidity with which the loop works allows the platform to move only a very small amount before correction is made. The small

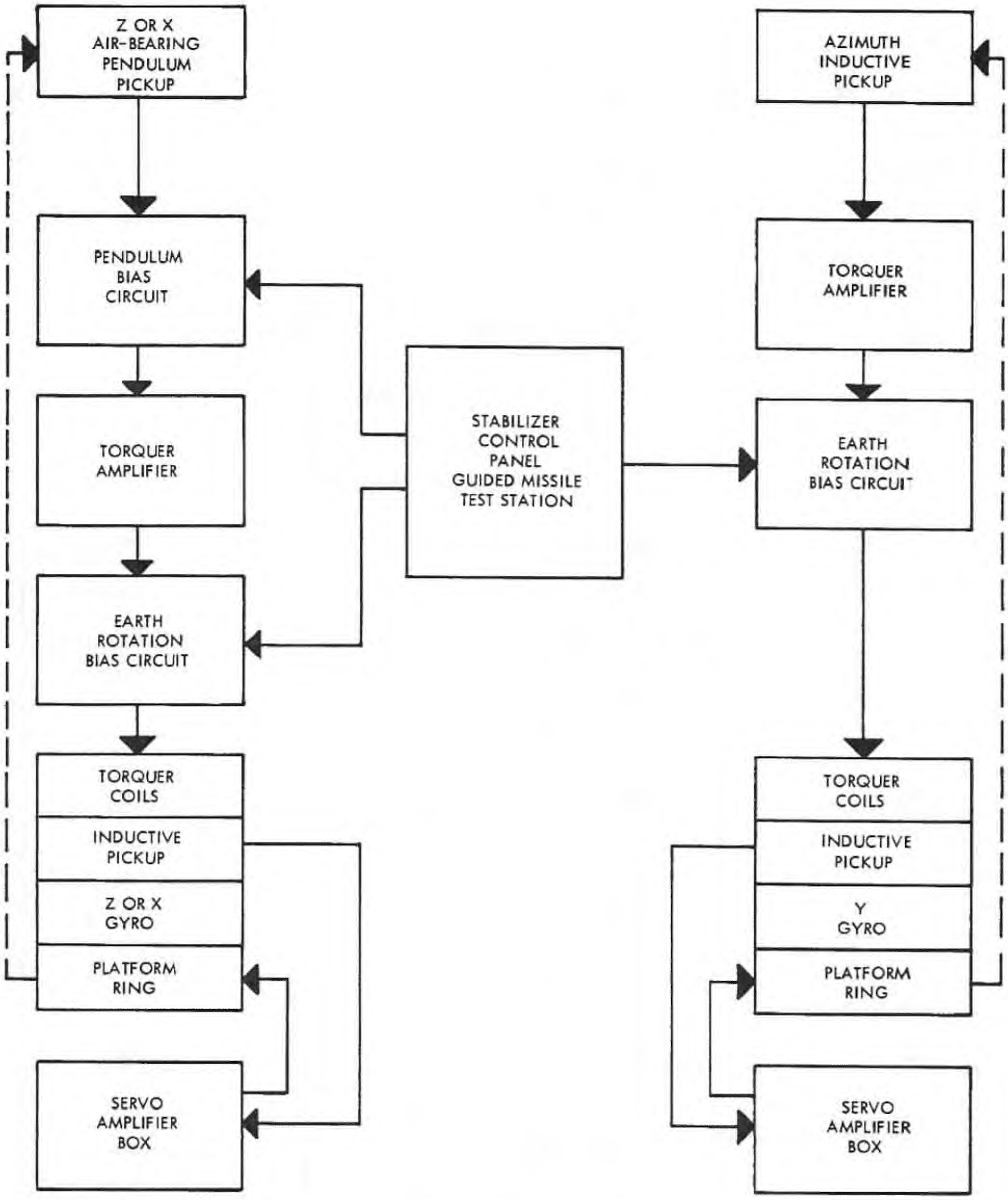


Figure IV-8 – Alignment Loops

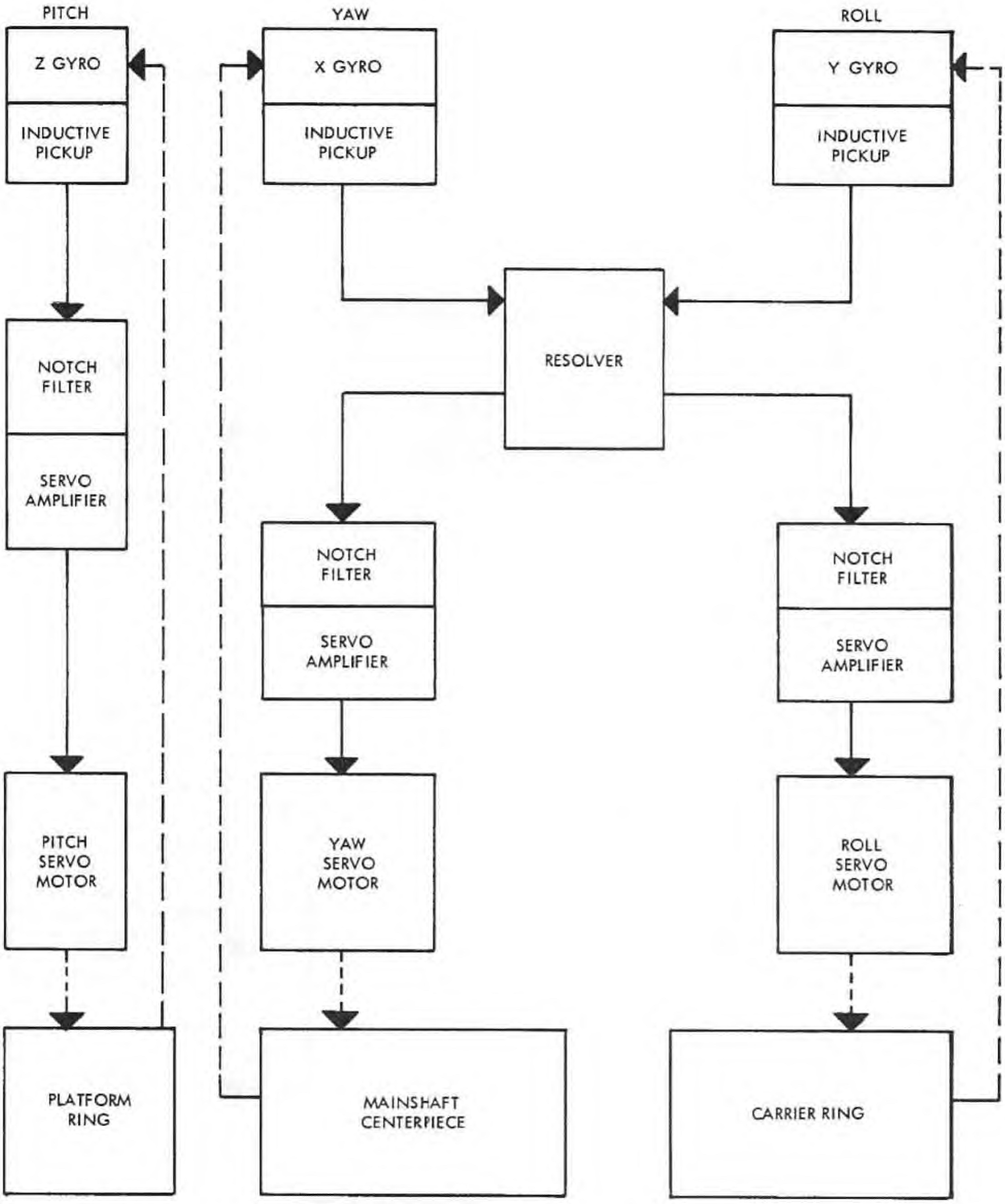


Figure IV-9 – Stabilization Loops

amount of error caused by the movement of the platform is corrected when the missile torque is removed. The servo motor will then drive to zero, or null out, the inductive pickup.

The yaw and roll channels work similarly, with the following exception: the outputs from the inductive pickups of the x and y gyros feed into a resolver. The output of the resolver is then fed to the servo amplifier. The function of the resolver is to apportion the input signals to the proper channel. The plane in which the roll and yaw servo motors apply countertorque changes in coincidence with the missile attitude about the pitch axis. Because a missile that is flying other than a true vertical or horizontal course will usually apply torque (to the platform) of such an angle as to cause at least two gyros to sense the torque, it is apparent that both servo motors would drive. The amount that each drives is dependent upon two factors: 1) the missile movement itself, as to whether it is a pure roll or yaw motion, or whether it is a complex motion involving both roll and yaw; and 2) the angle of the trajectory, or more accurately, the angle of rotor of the resolver. As an example, if the missile were flying at an angle of 45 degrees and it made a pure yaw motion, both the x and y gyros would sense the torque on the platform. Both gyros would produce an output to the resolver. However, due to the change of plane of the yaw and roll servo motors, the motor which we must drive to counteract this torque is the yaw servo motor only. Without the resolver, both would drive an equal amount and the resultant applied torque would not be exactly opposite to the applied torque and our reference would be lost. Because of the resolver action, however, the only output from the resolver will be that to the yaw servo amplifier and motor.

With the platform stabilized, the problem is to measure the deviation of the missile with respect to the reference. This is accomplished by using command potentiometers. With the body of a potentiometer attached to the mainshaft and the wiper attached to the carrier ring, any relative movement between the two will produce an output voltage. This voltage will be either a positive or negative voltage with respect to a reference voltage. The differential voltage is fed directly to the control computer, where it is used to correct the attitude of the missile. The wiper on the potentiometer is thereby repositioned and the output voltage is reduced to zero. All three attitude signals are derived identically in that the pitch, roll, and yaw attitude of the missile is measured by their respective potentiometers.

The use of the program transmission unit to provide the pitch programing necessary to tilt the missile into the ballistic trajectory works in conjunction with the pitch command potentiometer. The program transmission unit consists of the program motor, the program solenoid, the slip clutch, gearing, and the resolver. During flight, the program motor is turning constantly, but the shaft and gearing are attached to the motor by the slip clutch. Unless the solenoid is energized, the shaft is locked in position. The program device supplies the pulses necessary to energize the program solenoid. At a predetermined time of flight, it is desired to tilt the missile to coincide with the ballistic trajectory. Pulses are fed from the program device to the program solenoid, which is then energized and allows the shaft and gearing to turn. The length of the pulse

and the paw and ratchet assembly will allow the shaft to turn the equivalent of 1 degree of missile pitch. The turning of the shaft will do two things: 1) it will rotate the resolver rotor 1 degree; 2) through a series of gears, it will slide the wiper of the pitch command potentiometer to a position which will produce voltage indicative of 1 degree of error. The control computer responds to this voltage by causing the missile to pitch over 1 degree and thereby repositions the body of the pitch command potentiometer to a null point. This process continues according to a predetermined trajectory.

The range accelerometer is the device which senses the acceleration and deceleration of the missile along the range coordinate. The epsilon angle is that angle formed by the range coordinate and the local horizon. Since the range coordinate is different for each change in range of the target, the epsilon angle is also different. In order to measure acceleration along the range coordinate accurately, the angle of the range acceleration must be adjusted in such a manner that the true measuring direction is coincident with the range coordinate. The use of the stabilizer control panel and a motorized epsilon setting assembly of the range accelerometer enables a precise setting of the correct angle.

Since the lateral accelerometer is affected only by deviations of the missile to the left and right of the target, it is mounted on the platform without available means of adjustment.

Fundamentally, both the range and lateral accelerometers function identically. An acceleration of the missile reacts on the unbalanced mass, or weight, attached to the inner cylinder that contains the gyro and applies a torque to the spinning mass about the air bearing. This will torque the gyro and will cause the entire accelerometer assembly (with the exception of the platform mounting) to precess. Attached to this assembly is an output gear to which is coupled a synchro transmitter and a servo motor. The synchro transmitter rotor turns, thus providing a rotating electric voltage to the guidance computer. This rotating voltage is indicative of the attained velocity. Stated another way, the angular rotation of the accelerometer about the precessional axis in a given period of time is a measure of the velocity. Thus it can be seen that the first integration from acceleration to velocity is accomplished in the accelerometer.

The function of the accelerometer servo loop is to remove friction in the precessional axis of both accelerometers. The accumulation of frictions resulting from slip rings, ball bearings, and gearing would result in erroneous velocity information. When the unbalanced weight is acted upon by acceleration or deceleration, it applies torque to the inner cylinder that contains the gyro. The gyro will then begin to precess. Since there is friction about the precession axis, some means must be provided to counteract this friction. On the end of the inner cylinder of the accelerometer is an inductive pickup which produces an electrical output as a result of the friction when the accelerometer begins to precess. This voltage is amplified and fed to the servo motor on the accelerometer assembly. The torque that it applies to the precession gear is exactly enough to cancel out the friction. The precession axis, therefore, is considered to be essentially frictionless, thereby providing the guidance computers with the correct value of velocity.

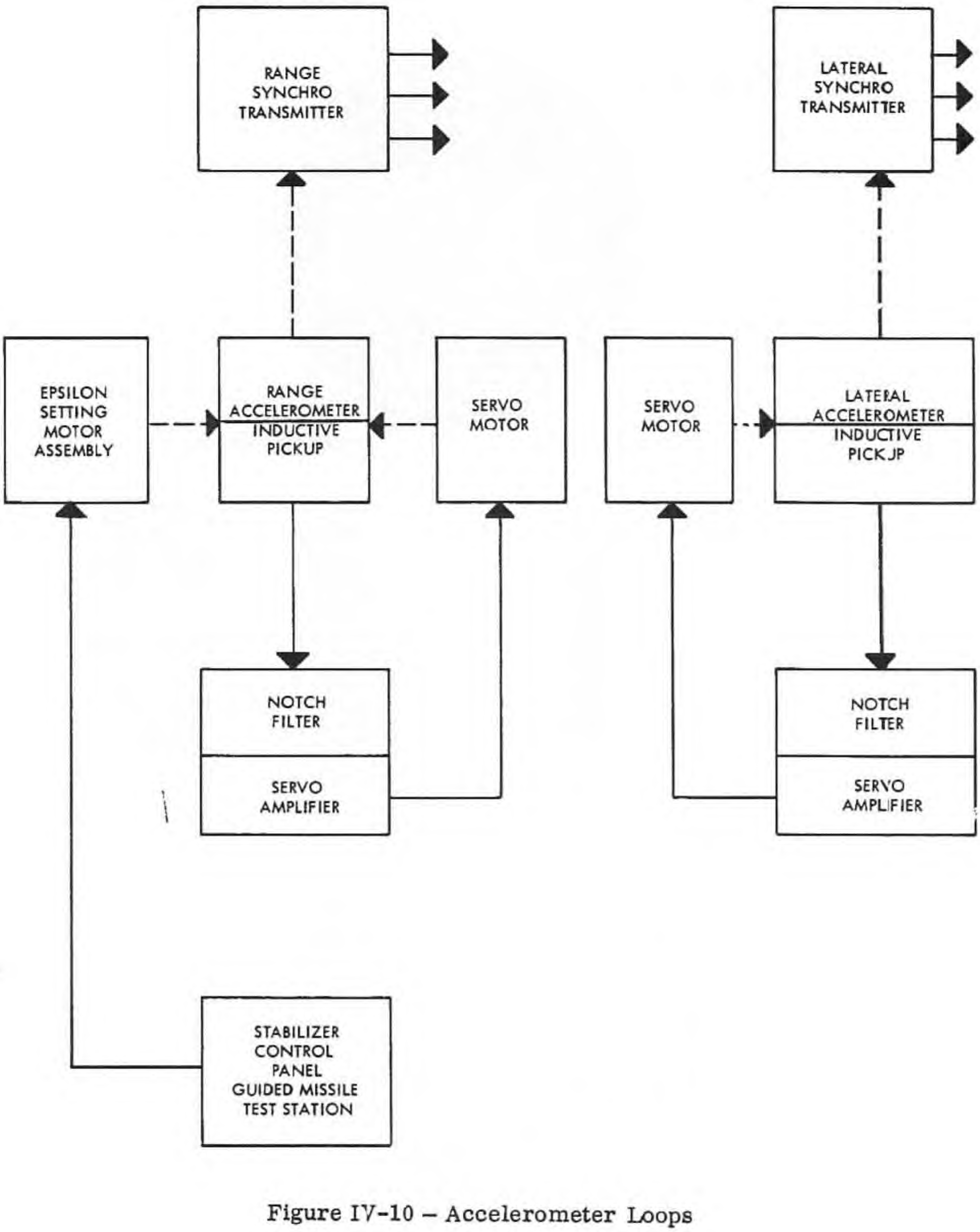


Figure IV-10 – Accelerometer Loops

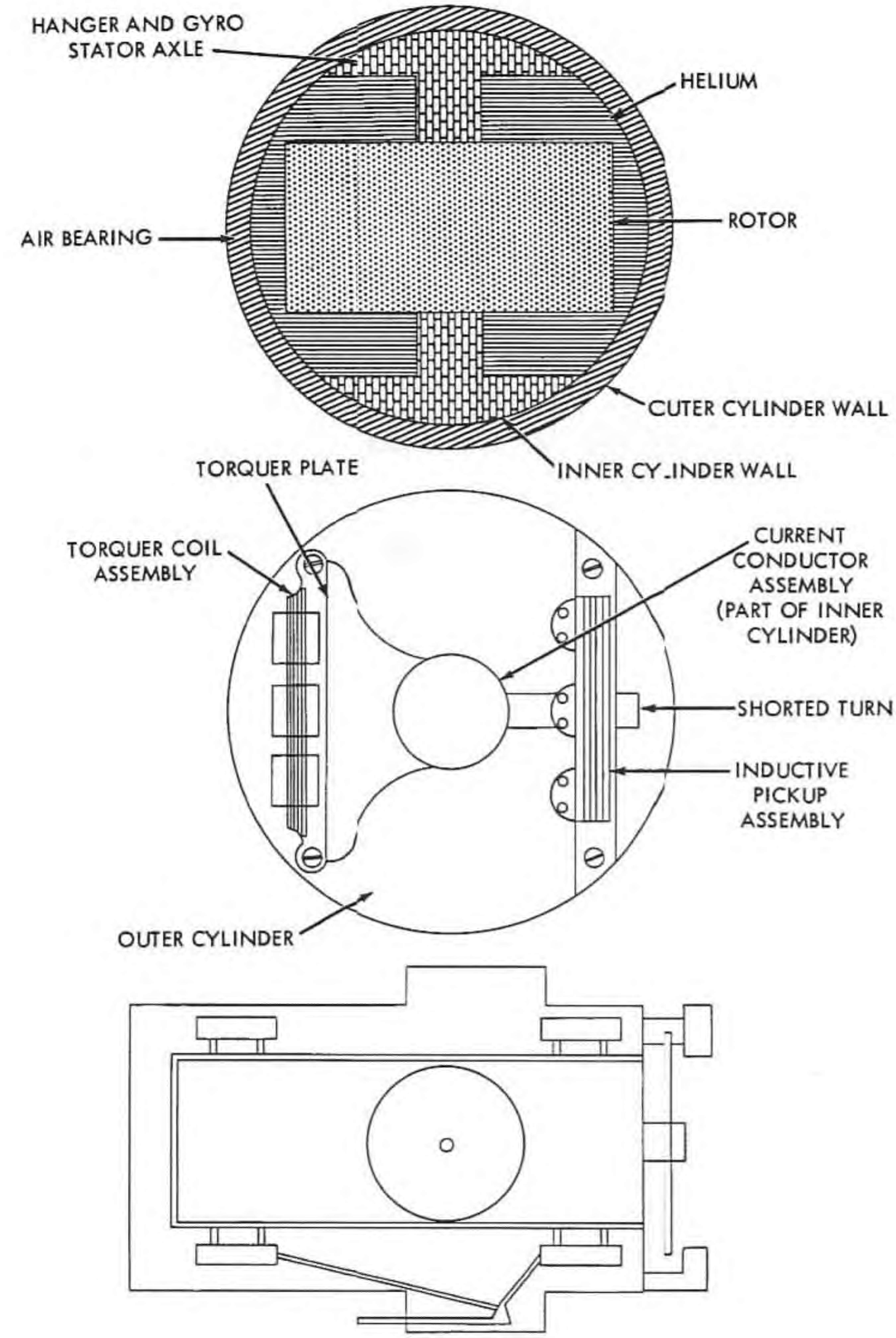


Figure IV-11 – AB-9 Gyro

GUIDANCE SYSTEM

The REDSTONE guidance system is divided into three sections: 1) lateral guidance computer, 2) the range guidance computer and 3) the cutoff computer.

The range and lateral guidance computers receive and store velocity information from the range and lateral accelerometers. In addition, the velocity information is integrated and the resulting displacement information is stored. At predetermined times during flight, this velocity and displacement information is fed into the control computer. The control computer then acts to cause the missile to alter its course to return to the predetermined trajectory. The cutoff computer utilizes the range velocity and displacement information to solve the cutoff equation. When this equation is solved (with some particular reservations), the thrust will be terminated.

Lateral Guidance

The problem of maintaining the missile's center of gravity on the trajectory is a function of the guidance computers. In the case of the lateral guidance computer, it serves to provide a corrective signal when the missile deviates to the left or right of the trajectory, from launch to cutoff plus 1.5 seconds. From cutoff plus 1.5 seconds to re-entry (Q), any deviation of the missile from the trajectory is sensed, and rather than providing corrective action immediately, the information is stored. At re-entry, this information is fed into the control computer, and the missile begins to make the necessary corrective maneuver to return to the intended trajectory. This last phase is referred to as terminal guidance.

Deviations from the trajectory can be caused by atmospheric conditions, thrust decay, separation, and other factors. The deviations are sensed by the use of integrating accelerometers. The action of the accelerometer is to precess whenever the missile accelerates or decelerates in the measuring plane of the accelerometer. For this reason, the lateral accelerometer is mounted on the stabilized platform in such a position as to sense acceleration and deceleration either to the right or left of the trajectory.

When a vertically rising missile is shifted to the left of the trajectory, the lateral accelerometer precesses at a rate proportional to the acceleration and in a direction dependent upon the direction of acceleration. The output coupling device is a synchro transmitter; the rotor is rotated mechanically by the precession of the accelerometer. The rotating rotor of the synchro transmitter will thus cause the stator voltage to rotate electrically at a rate proportional to the velocity. This rotating electrical signal voltage sets up a rotating magnetic field in the stator of the control transformer. A voltage is thereby induced into the rotor of the control transformer and this voltage, in turn, is fed to a servo amplifier, where it is amplified and used to drive a servo motor. The servo motor drives a gear train which performs three functions: 1) repositions the rotor of the control transformer to zero out the input to the servo amplifier, 2) positions the wiper of the lateral velocity control potentiometer to a point such

that the voltage appearing on the wiper is indicative of the missile velocity, and 3) drives the lead screws of the ball-and-disc integrator. The ball-and-disc integrator performs the second integration, that of velocity with respect to time, and the output drives a gear train which positions the wiper of the displacement potentiometer. The position of the wiper determines the output voltage, and this voltage is then indicative of the displacement from the trajectory. Thus, two voltages are fed to the control computer: 1) lateral velocity signal voltage and, 2) lateral displacement signal voltage. These voltages will continue to increase as long as the missile is accelerating. Once the missile attains a constant velocity, the lateral accelerometer will stop precessing, the servo motor will stop driving the gear train, and the wiper on the velocity potentiometer stops moving. The ball-and-disc integrator output is still rotating, however, the wiper on the displacement potentiometer continues to move, and the displacement voltage continues to increase.

In Phase I (launch to cutoff) of the flight, however, the control computer accepts these input voltages and produces the necessary driving voltages to drive the air rudders in a direction which will return the missile to the intended trajectory. When the rudders move, the missile will decelerate laterally, the lateral motion of the missile will stop, and it will accelerate back toward the intended trajectory. As this happens, the lateral accelerometer will sense the deceleration and acceleration and will precess in the opposite direction. As it does, the servo system in the lateral guidance computer turns in the opposite direction, thus moving the wiper back toward the zero voltage point and repositioning the lead screws of the ball-and-disc integrator so that the displacement potentiometer wiper is also returned to zero. At this time, the missile will be back on the intended trajectory and the guidance system will become static until there is another disturbance.

During Phases II and III, the accumulated errors in velocity and displacement are stored on the potentiometers rather than being fed to the control computer. At reentry (Q), the potentiometers are zeroed as in Phase I.

Range Guidance

The primary purpose of the range guidance system is to assure that the missile does not overshoot or undershoot the target. Included in the system is the range accelerometer, the range computer, and the cutoff computer.

The range accelerometer is mounted on the stabilized platform; the range and cutoff computers are mounted on a chassis in the range computer box.

The information relative to this system is the velocity and displacement of the missile along the range coordinate. Therefore, the accelerometer is mounted on the stabilized platform at an angle such that the true measuring direction is coincident with the range coordinate. The angle subtended by the range coordinate and the local horizon is referred to as the epsilon angle.

The problem of putting the missile into a ballistic trajectory so that its point of impact can be determined involves some special consideration that must be provided for in the range computer. Preset information is inserted into the range computer's velocity and displacement potentiometers.

Since the missile launching site is physically ahead of the theoretical launch site (that site which would be used in conjunction with the reference trajectory to place a missile on the selected target) and the REDSTONE Missile starts from zero velocity (rather than a fixed specific velocity), a negative velocity and a positive displacement value are preset into the range computer and cutoff computer velocity and displacement potentiometers, respectively. In addition, preset values which allow for the effects of thrust decay, separation of the body and thrust unit, and air drag from cutoff to re-entry are inserted.

As the missile leaves the launcher, the range accelerometer begins to precess. As it does, the range servo motor begins to reposition the velocity and displacement potentiometers toward zero. When cutoff occurs, the preset velocity and displacement is considered to be cancelled out (the missile has reached the velocity and displacement of the theoretical missile). The only values remaining would be those of the effects of thrust decay, separation, and air drag.

From cutoff to re-entry, the change in range velocity is relatively small (and if conditions were exactly as assumed for in the presetting, the range computer would be zeroed at re-entry). At re-entry, any range information that remains on the range velocity and displacement potentiometers would be fed into the control computer, where corrective action would be initiated to zero out these errors.

Cutoff Computer

The function of the cutoff computer is to compute the proper time for thrust termination (engine cutoff) and to initiate the action. The computer is a magnetic amplifier type; preset negative velocity and positive displacement information is supplied to the computer from the cutoff velocity and displacement potentiometers. In addition, bias voltages representing calculated time from cutoff to re-entry and a cutoff constant which allows for the effects of thrust decay, separation, and air drag are fed into the computer. The preset velocity and displacement information must be zeroed out in the cutoff computer. Since the velocity and displacement are continually changing as the missile is ascending, the cutoff equation is solved several times. In order to prevent premature cutoff, a cam-operated switch which is in series with the cutoff relay in the cutoff computer must be closed. The cam switch is operated when the missile has reached within -55 to +60 meters per second of the desired velocity. The first time the cutoff equation is solved after the cam switch is operated (and providing the X+96 seconds relay is closed), the cutoff relay (in the control distribution) will be energized, thus initiating engine cutoff. After cutoff, the cutoff computer serves no function.

CONTROL SYSTEM

The REDSTONE control system as previously mentioned, consists of the control computer, the relay box, and actuators. The control computer receives the seven guidance and control signals and amplifies and mixes these signals in the right proportion for distribution to the control surface. Phi signals (pitch, roll, and yaw) pass through R-C networks and into the respective preamplifiers, where they are mixed with any incoming guidance signals. Lateral guidance signals will be fed to the yaw preamplifier, and the range signals will be fed to the pitch preamplifiers. The outputs of the preamplifiers are fed into the main amplifiers. The output of the pitch preamplifier is fed into main amplifiers II and IV. The yaw preamplifier feeds main amplifiers I and III. All four main amplifiers are fed by the roll preamplifier.

All amplifiers in the computer are magnetic amplifiers. Through the use of the R-C networks, the incoming phi signal can be broken down into its two component parts. The current flowing into the preamplifier through the resistance portion of the network represents the magnitude of error. A second current flows into the preamplifier through the capacitance portion of the network, which represents the rate of change of the error signal.

The output of the preamplifier will be a result of not only how much error has occurred but also the rate at which it occurred. The incoming velocity signals from the guidance computers go directly to the preamplifiers. However, the displacement signals are placed across two potentiometers which are driven by the step motor. At "Q" the step motor is driven by the dive program from the program device and, in turn, drives the wipers of the potentiometers from the zero position to the maximum position. This enables the displacement errors that have occurred during flight to be corrected for gradually instead of inserting the entire error into the system at once.

Also contained within the control computer are various relays. The purpose of these relays is to switch circuit values in order to change the gain and response of the control system to compensate for changing missile velocity, configuration, and aerodynamic conditions. The output from the four main amplifiers is fed to the relay box. The relay box, as its name implies, consists of relays which convert the small-amperage signal coming from the main amplifier of the control computer into the high amperage necessary to drive the actuator motors. The incoming signal energizes a polarized relay which, in turn, energizes a heavy-duty relay that connects the 28-volt battery to the actuator motor. As the actuators drive the vanes outward, a potentiometer (beta potentiometer) within the actuators feeds vane position information back into the main amplifier in the control computer, where it is compared to the original error. Since there are four channels, the relay box contains four polarized relays and four heavy-duty relays (one polarized and one heavy-duty relay for each of the four channels). The output of the relay box is 28 volts dc from the general network battery connected to the actuators through the heavy-duty relays. The actuators consist of a 28-volt d-c motor, a gear train, an output member, two potentiometers, and four microswitches. The gear train gives a reduction of approximately 600 to 1. The two potentiometers provide

vane position information. The beta potentiometer feeds its information back to the control computer, and the measuring (M) potentiometer feeds information to the telemetry circuits during flight and to the ground checkout equipment during checkout.

POWER

There are two phases of operation of the REDSTONE system power sources. The first phase involves the use of ground support equipment, in addition to a portion of the missile power equipment, to supply necessary voltages to check out and prepare the missile for launching. The second phase is initiated by a step in the countdown procedure called power transfer. During the second phase, all power used on the missile is supplied by sources aboard the missile. The following list contains all the power sources used in the two phases:

Phase I

60-kw diesel generator – 208-volt/120-volt, 60-cps, 3-phase
2 aircraft energizers – 28-volt d-c
60-volt d-c power supply
2 inverters – 115-volt, 400-cps, 3-phase

Phase II

2 self activating batteries – 28-volt
60-volt d-c power supply
Inverter, 115-volt, 400-cps, 3-phase

In addition to the above equipment, the following panels, located in the guided missile test station and the power distribution trailer, are necessary for energizing, controlling, and monitoring these components:

Precision generator
Inverter control panel
Electric power panel
Power supply panel, 28-volt d-c

Phase I

The function of the ground power equipment is to supply the necessary voltages to be used for checkout, testing, and launch preparation.

The primary power source is the 60-kw diesel generator. This generator supplies 208-volt, 3-phase, 60-cps voltage to the a-c distributor box, the battery service trailer and the power distribution trailer. The generator is driven by a 6-cylinder Cummins diesel engine that supplies 160 hp at 2,500 rpm. Its normal operating speed is approximately 1,850 rpm. This engine drives a General Electric synchronous generator which provides a 208-volt, 3-phase, 60-cps output from a Y-connected transformer.

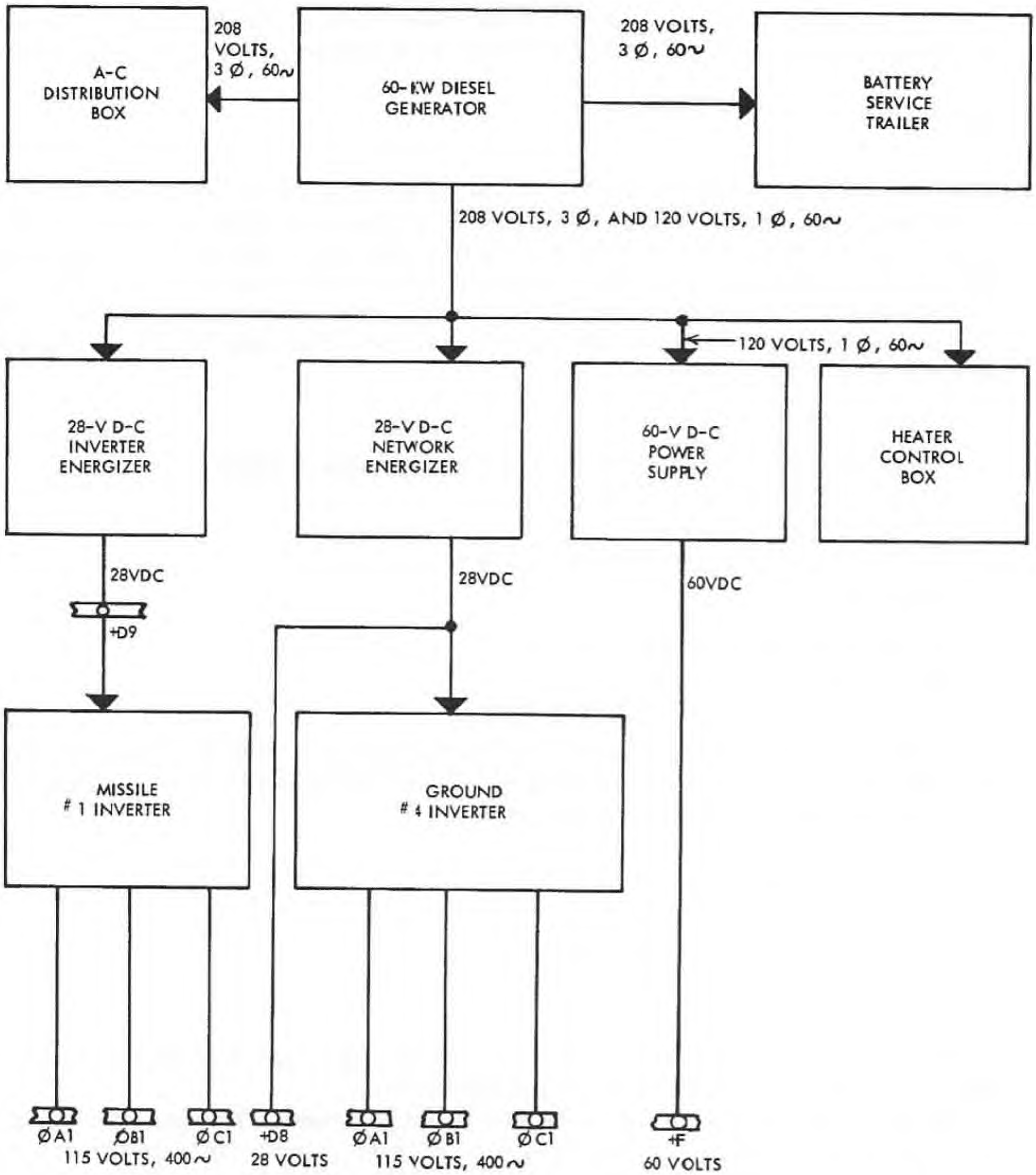
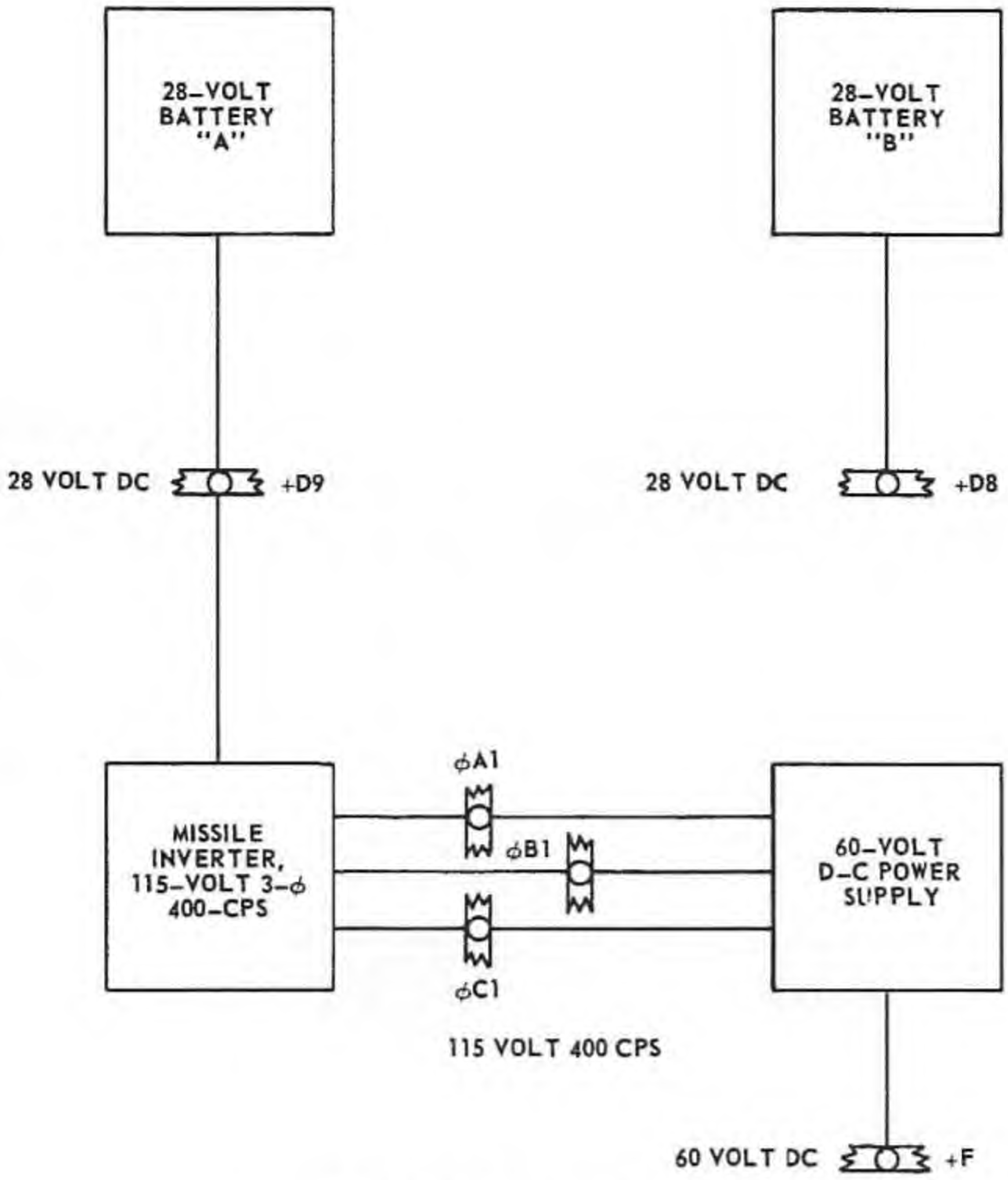
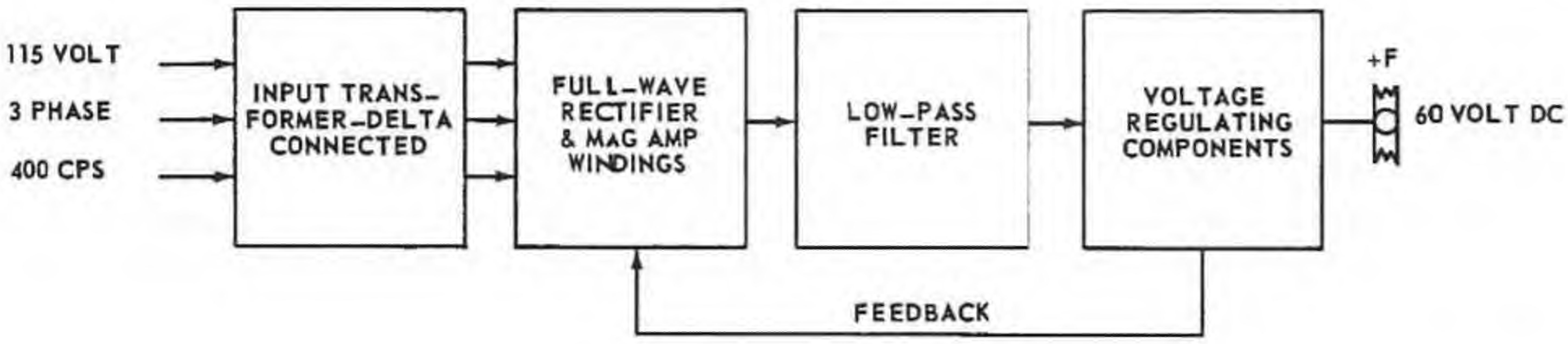


Figure IV-12 – Primary Power Source



MISSILE VOLTAGE DISTRIBUTION



60-VOLT D-C MISSILE POWER SUPPLY

Figure IV-13 – Missile Power Components and Distribution

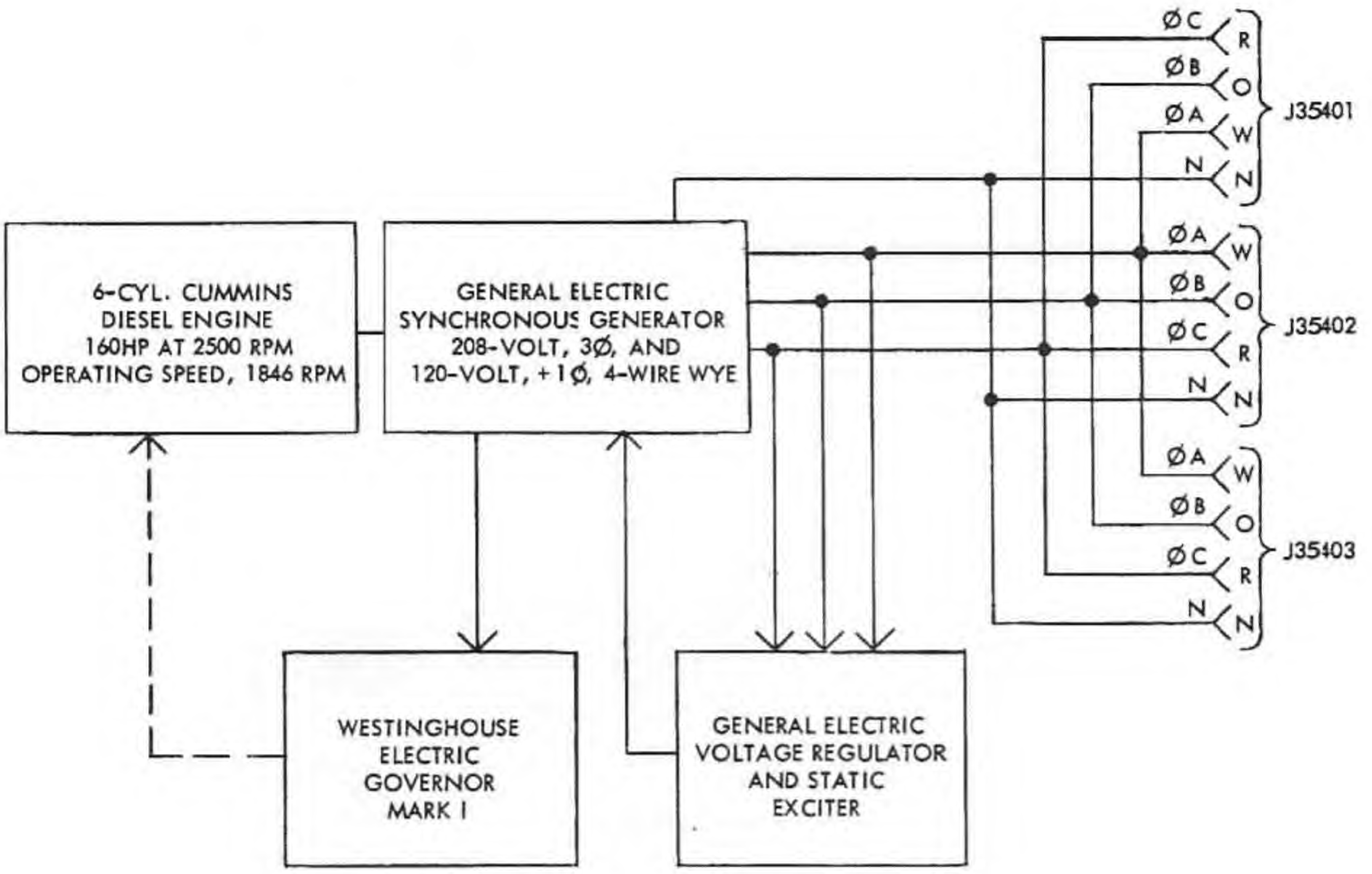


Figure IV-14 – 60-KW Generator

The 4-wire output, in conjunction with the 208 volts (phase-to-phase), also makes available 120 volts (phase-to-neutral). It employs both frequency and voltage regulation. The frequency regulation is accomplished by a Westinghouse Electric governor and the voltage regulation by a General Electric voltage regulator and static excitor.

The voltage supplied to the a-c distribution box is fed to various pieces of ground support equipment such as the alc and the LOX trailers, the hydrogen peroxide vehicle, and the guided missile test station.

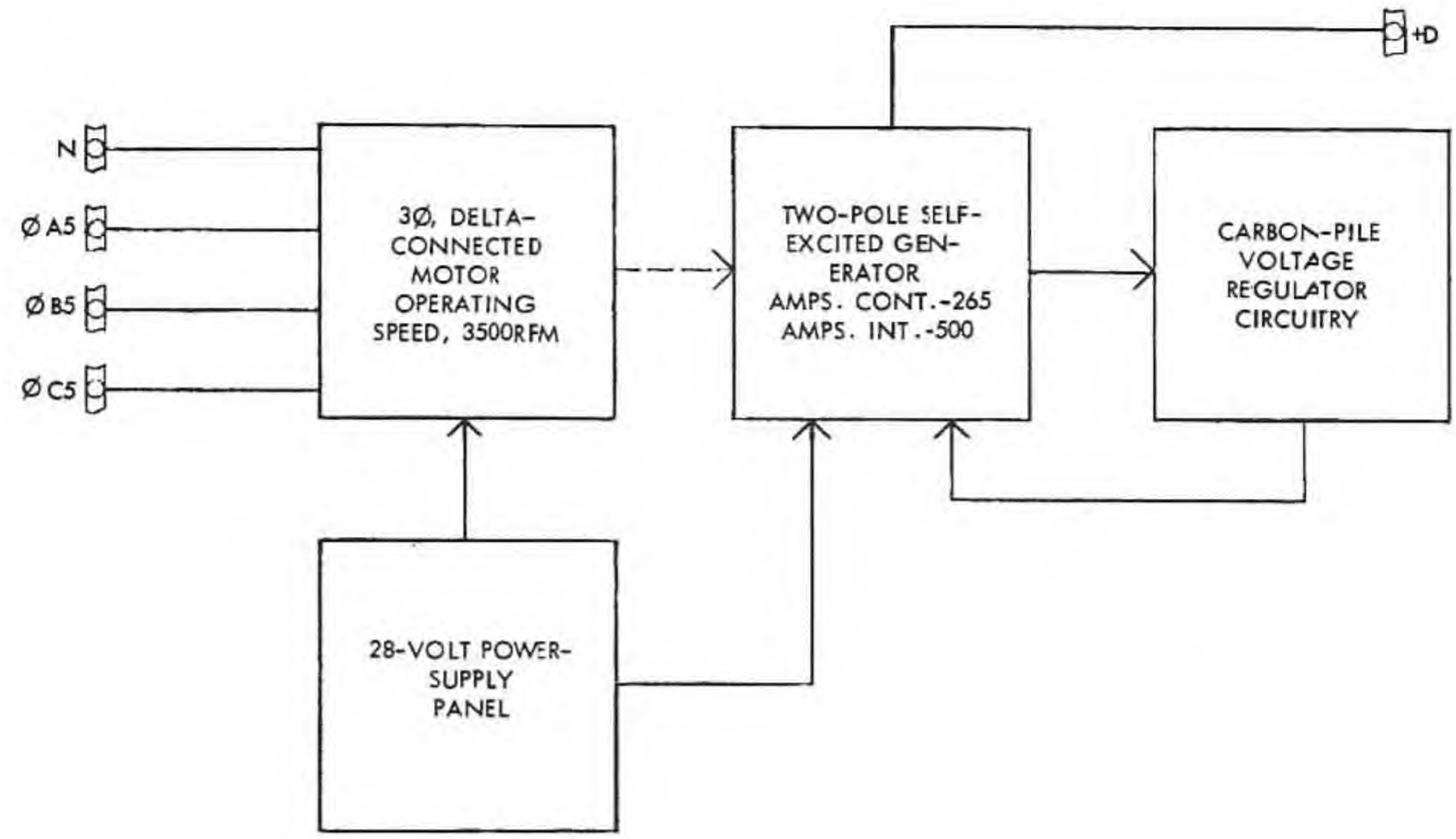


Figure IV-15 – 28-Volt Energizer

In the power distribution trailer, the 208-volt, 3-phase voltage is fed to the two aircraft energizers. These motor generators provide the system with 28 volts dc. They consist of a 3-phase delta-wound motor driving a generator which provides 28 volts dc at up to 265 amperes continuously. It utilizes a carbon pile regulator to provide voltage regulation. The controls for energizing, monitoring, and adjusting are located on the 28-volt d-c power supply panel. The outputs from the generator are fed to two busses. The network energizer is connected to the +D1 bus which feeds the +D8 bus in the missile. This bus is used primarily for operating relays and the rotary actuators. The other energizer provides voltage to the +D2 bus, which feeds into bus +D9 on the missile. This bus is used primarily for operating inverter 1 on the missile.

The 60-volt d-c power supply is used to provide voltage for the command potentiometers, the velocity and displacement potentiometers, and the beta feedback potentiometers. Its input is 120 volts, 60 cps, single phase and has an output of 54 to 66 volts dc at up to 2 amperes. It uses a magnetic amplifier type voltage regulator. Its output is fed to the +F bus (Figure IV-16).

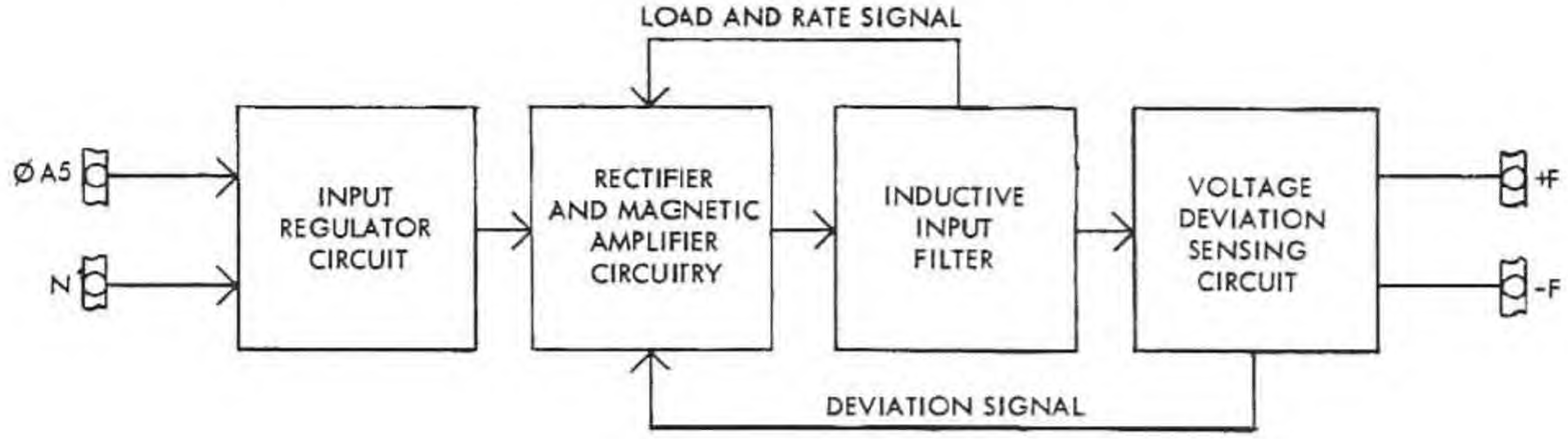


Figure IV-16 – 60-Volt Regulated Power Supply

Inverter 4 is used to provide 115-volt, 3-phase, 400-cps voltage to the ground equipment test fixture. The inverter consists of a 28-volt compound wound motor which drives a 3-phase, Y-connected generator. Included also is a regulator which contains both frequency- and voltage-regulator circuits. By the use of a frequency discriminator circuit, a change in frequency can be quickly detected and the current in the shunt winding of the motor increased or decreased to alter the speed of the motor, thus changing the frequency. A voltage discriminator circuit detects changes in output voltage and controls the current in the generator field, thus controlling the output voltage.

The electric power panel located in the guided missile test station contains meters to monitor the two 28-volt d-c busses. Also included on this panel is a meter which is used to monitor the 60-volt d-c command voltage supply and a switch which energizes a relay to apply the voltage to the +F bus.

Inverter 4 is used to provide 115-volt, 3-phase, 400-cps voltage to the ground equipment test fixture. The inverter consists of a 28-volt compound wound motor which drives a 3-phase, Y-connected generator. Included also is a regulator which contains both frequency- and voltage-regulator circuits. By the use of a frequency discriminator circuit, a change in frequency can be quickly detected and the current in the shunt winding of the motor increased or decreased to alter the speed of the motor, thus changing the frequency. A voltage discriminator circuit detects changes in output voltage and controls the current in the generator field, thus controlling the output voltage.

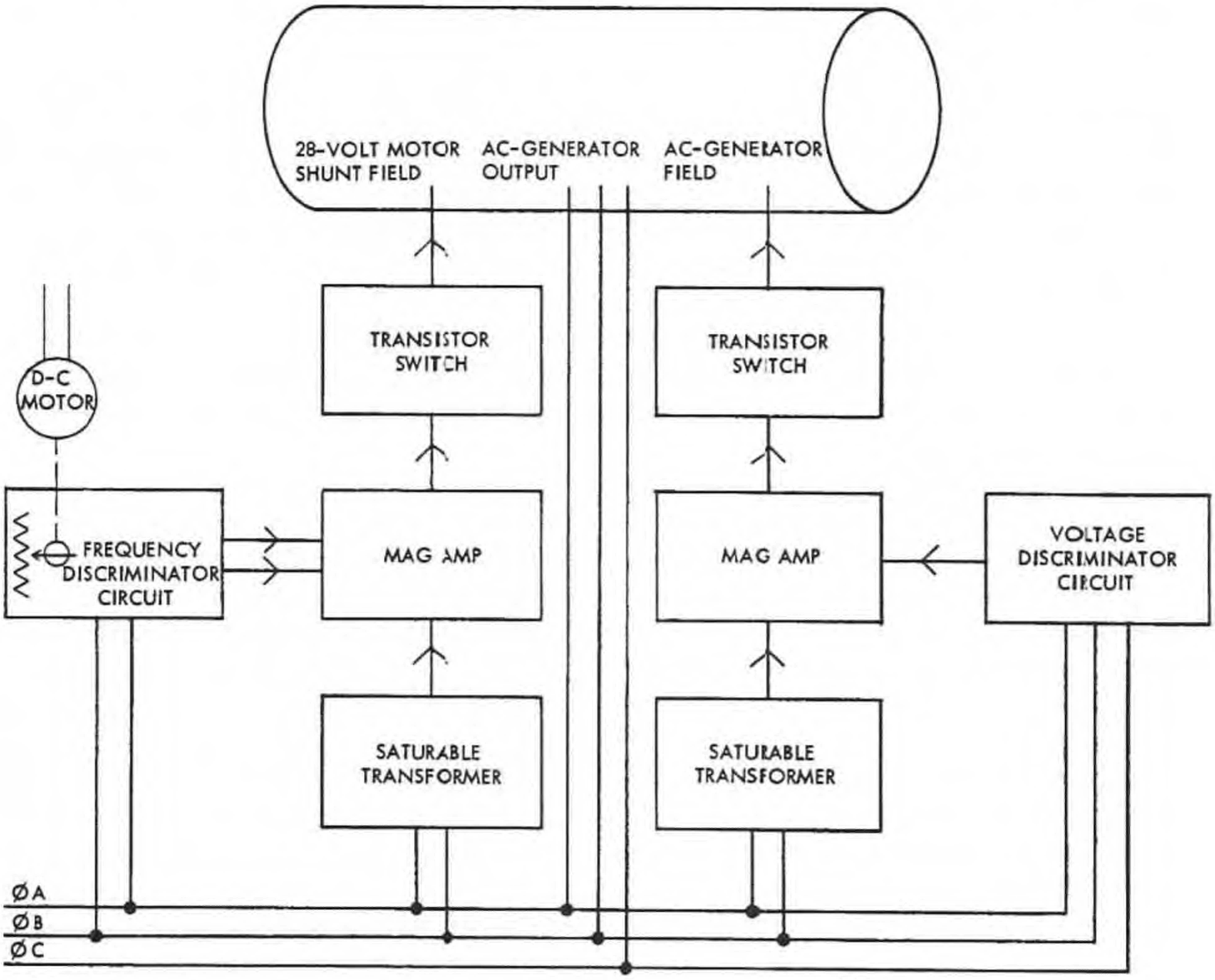


Figure IV-17 – Mod O Inverter Block Diagram

The function of missile power components is to supply the a-c and d-c voltages necessary to sustain the missile in flight. In addition, the a-c supply furnishes voltage to the panels of the guided missile test station when the missile is being checked out.

The two 28-volt batteries, the 60-volt d-c power supply, and inverter 1 comprise the missile power supply system.

The two 28-volt batteries aboard the missile are remotely activated by the Guided Missile Test Station. Both batteries are enclosed in one common battery box and activated simultaneously. The "A" battery supplies power to the missile inverter; the "B" battery supplies power to the mechanical actuators and the relays of the missile system.

Both batteries contain 20 zinc-silver oxide cells with a total of 2000 cc potassium hydroxide as the electrolyte. Prior to battery activation, the electrolyte is stored in copper tubing that encircles the batteries. The activation signal from the ground fires two explosive squibs which build up pressure, forcing the electrolyte through the manifold into the battery cells. Activation time is approximately 5 minutes; the standby charge time is 12 hours. Battery "A" is connected to bus D9 and battery "B" is connected to bus +D8 at power transfer.

The 60-volt power supply provides 60 volts d.c. at a maximum of 2 amperes to the +F bus at power transfer. This voltage is used for the command potentiometers, beta feedback potentiometers, and the velocity and displacement potentiometers of the guidance computers.

The 115-volt, 60-cycle, 3-phase input is applied to the delta-connected power transformer. A full-wave rectifier is used in each phase, and the output is fed through a pi-type filter. A magnetic amplifier is utilized to provide voltage regulation.

Inverter 1 is identical to inverter 4, located in the power distribution trailer. In addition to the regulator circuits incorporated on the inverter, an inverter control panel is located in the guided missile test station. This panel, in conjunction with the precision generator, will compare the frequency of inverter 1 with the precision generator output voltage. If there is a difference of frequency, the inverter control panel will operate a switch which will apply a voltage to a frequency control motorized potentiometer in the inverter-regulator. This will cause the wiper of the potentiometer to move in one direction or the other, thus changing the resistance in the discriminator circuit. This will cause the frequency regulator circuit to change the current in the shunt winding of the motor, thus changing the frequency to that of the precision generator.

CHAPTER V

PROPULSION SYSTEM

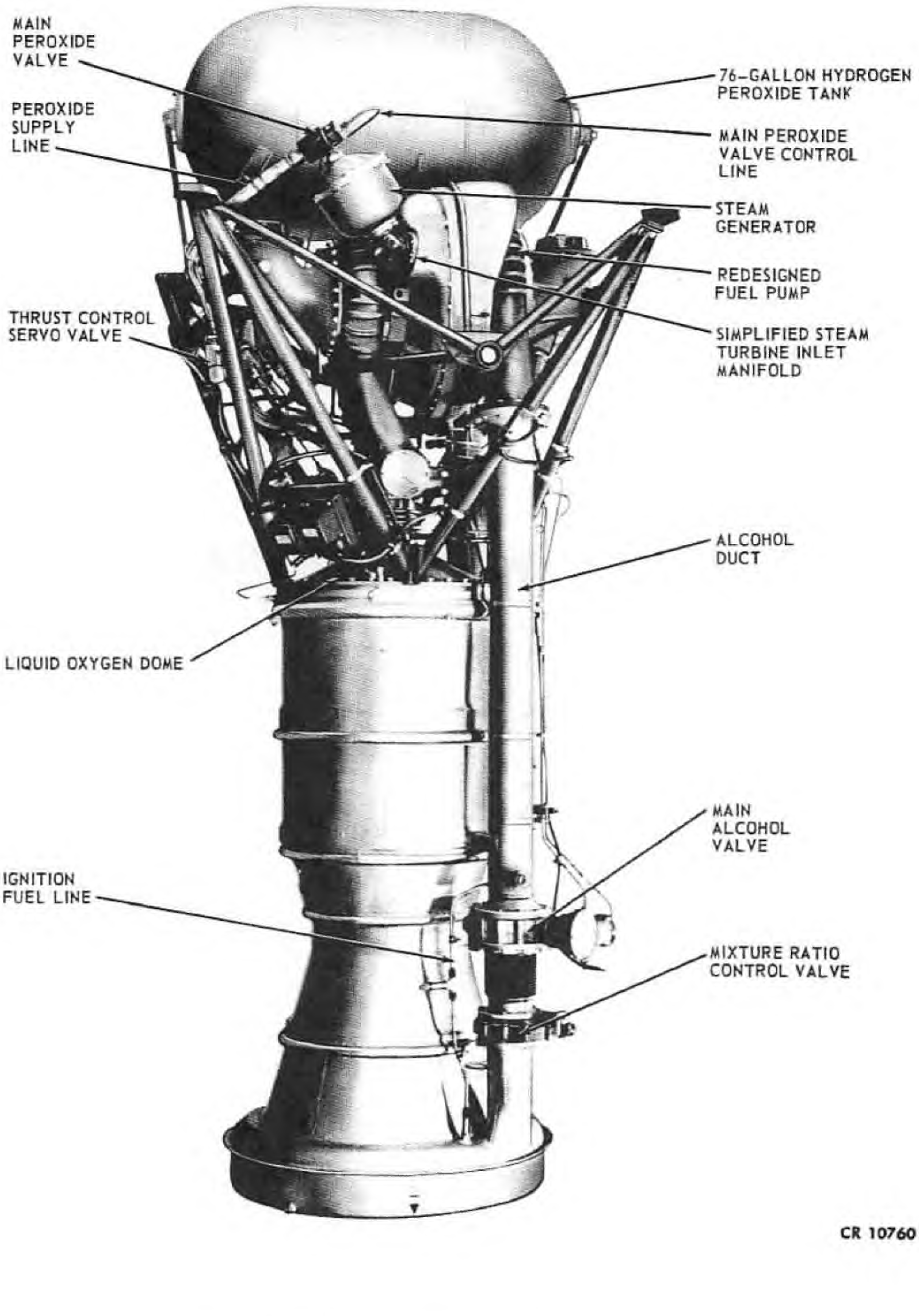


Figure V-1 – A-7 Rocket Engine

CHAPTER V
PROPULSION SYSTEM

GENERAL

The powerplant of the REDSTONE missile is a bipropellant liquid rocket engine manufactured by the Rocketdyne Division of North American Aviation Corporation.

This engine, which is an improvement over the German V2 engine, has a fixed thrust of about 78,000 pounds. This thrust can be generated for a period of 121 seconds, if necessary, but actual service use is less. The energy for this thrust is provided by a 75 per cent concentration of ethyl alcohol and LOX (the two propellants). These propellants are transferred from the missile tanks to the engine combustion chamber by high-pressure pumps which are driven by a steam turbine.

Although this engine is a fixed-thrust engine, small variations in thrust caused by ambient conditions can be corrected. This correction makes it possible to keep the thrust constant for guidance purposes and effectively removes a variable which would further complicate the system. The rocket engine, like other more familiar powerplants, needs several supporting systems for starting, stopping, and operating efficiently.

STEAM SYSTEM

This system is better known as the H_2O_2 system, or hydrogen peroxide system. Hydrogen peroxide, when decomposed rapidly, forms high-pressure, high-temperature steam. In the REDSTONE Missile the peroxide system is used to drive the propellant pumps by means of a steam turbine. The steam system has the following major components; a 76-gallon tank, a steam generator, a shutoff valve, a variable control valve, a pressurizing and venting valve, and an exhaust system.

When the launch start button is pushed, the pressurizing valve is opened and air is released at a pressure of 550 to 650 psi into the tank. The system is now static until the shutoff valve is opened. The peroxide flows through the variable control valve and into the steam generator, which is also known as the steam "pot". Inside the steam generator are potassium permanganate pellets. These pellets act as a catalyst, causing the peroxide to decompose rapidly into water and oxygen. This action releases a tremendous amount of heat and forms high-pressure, high-temperature steam. The steam is directed to the turbine, which in turn drives the fuel and LOX pumps. The pumps are attached to the same shaft. After passing through the turbine, the steam

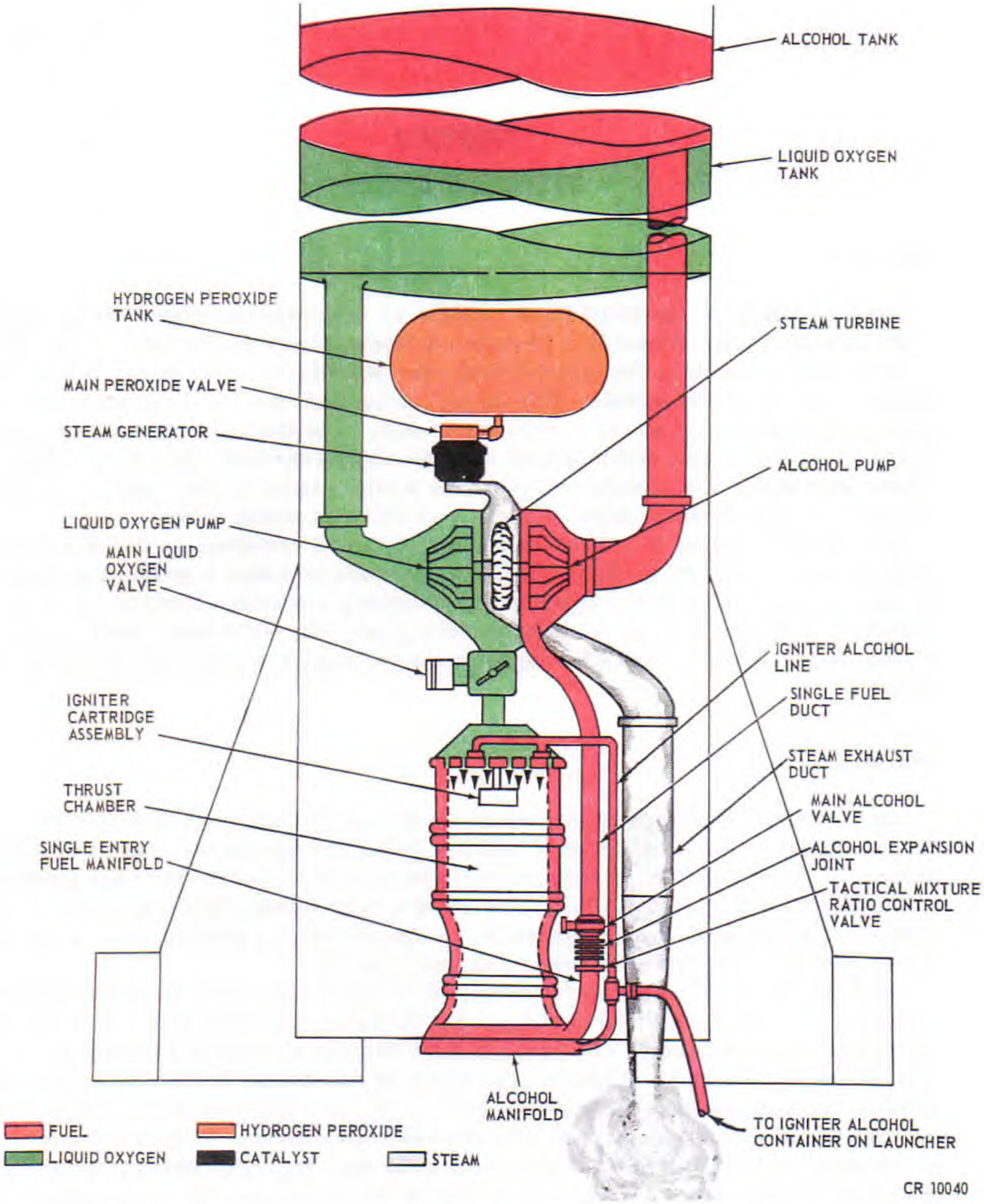


Figure V-2 – Propellant and Hydrogen Peroxide Flow Diagram

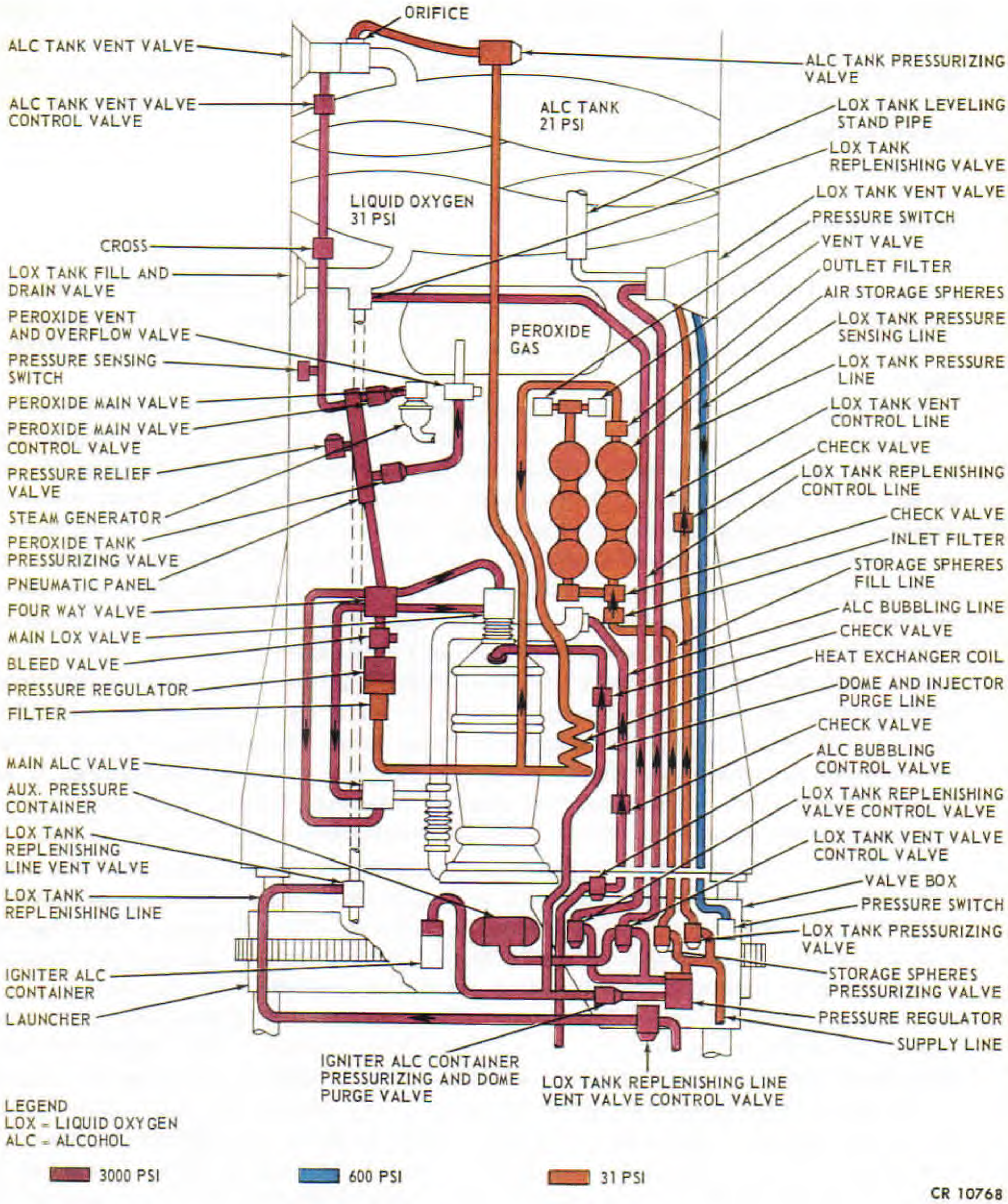


Figure V-3 – Pneumatic System

goes into the exhaust duct, where it vaporizes a small amount of LOX for the purpose of pressurizing the LOX tank of the missile, and to expand the main missile air supply as an economy measure. This is done through a unit called a heat exchanger, which is located in the exhaust duct. The steam is then sent overboard, adding a few hundred pounds of thrust to the missile.

PROPELLANT SYSTEM

The propellant system transfers the fuel and oxidizer from the missile tanks to the thrust chamber under pressure. The system consists of two tanks, two centrifugal-type pumps, two on-off control valves, a mixture ratio control valve, and the engine passages.

The two tanks are a part of the missile structure; the fuel tank is located immediately above the oxidizer tank. The fuel passes through the oxidizer tank (by way of a pipe) to the fuel pump. After leaving the fuel pump, the fuel is held from entering the engine by the closed main fuel valve. Following the main fuel valve is the mixture ratio valve. This valve is adjusted before flight to compensate for ambient effects on the fuel. Because alcohol density varies with temperature and pressure, varying amounts of fuel must be admitted into the engine in order to assure the proper thrust. From the mixture ratio valve, the fuel flows to a section, incorporated in the engine, known as the fuel manifold. This section collects the fuel and sends it up through the engine chamber walls. Fuel flowing through the walls of the engine serves two purposes. The primary purpose is to cool the engine chamber walls; no metal can withstand the 5,000°F temperature within the combustion chamber for very long. The fuel flows through the chamber very fast and absorbs so much heat that the temperature in the outside wall is maintained at about 125°F. The second purpose is to increase the thermal efficiency of the fuel by this heat absorption. Over-all system efficiency is thereby increased.

The engine passages lead to a part of the engine known as the injector. The injector is a steel plate that contains internal passages and rings. These rings have holes drilled at an angle so as to send a stream of fuel against a stream of fuel alternating with a ring with liquid oxygen doing the same. In this manner, the fuel and oxidizer is mixed at a given distance from the plate and forms a combustible mixture.

LOX flow is from the tank through the LOX pump and is stopped by the main oxidizer valve. From the valve, the LOX flows to the front (or top) of the engine and into the LOX dome and injector. The dome is just above the injector and serves as a manifold.

The injector performs two other functions. The outermost ring sends fuel down the thrust chamber inner wall and assists in the cooling of the thrust chamber. LOX and fuel alternate with the final ring (of twenty rings) discharging LOX. The other function is to assist in starting the engine. The center of the injector has a surface known as the ignition disc. Into this surface is fastened a pyrotechnic igniter which is similar to a flare. This surface also receives fuel from an external start tank. This fuel is directed through separate passages in the injector.

TURBOPUMP

The turbopump is the heart of the propulsion system. Without it, tank weight would be prohibitive because the tanks would have to be heavy in order to be sufficiently strong to permit adequate pressurization.

The turbopump consists of a turbine, a gear reduction section and two centrifugal pumps. These pumps are coupled to the turbine shaft and are driven at the same speed.

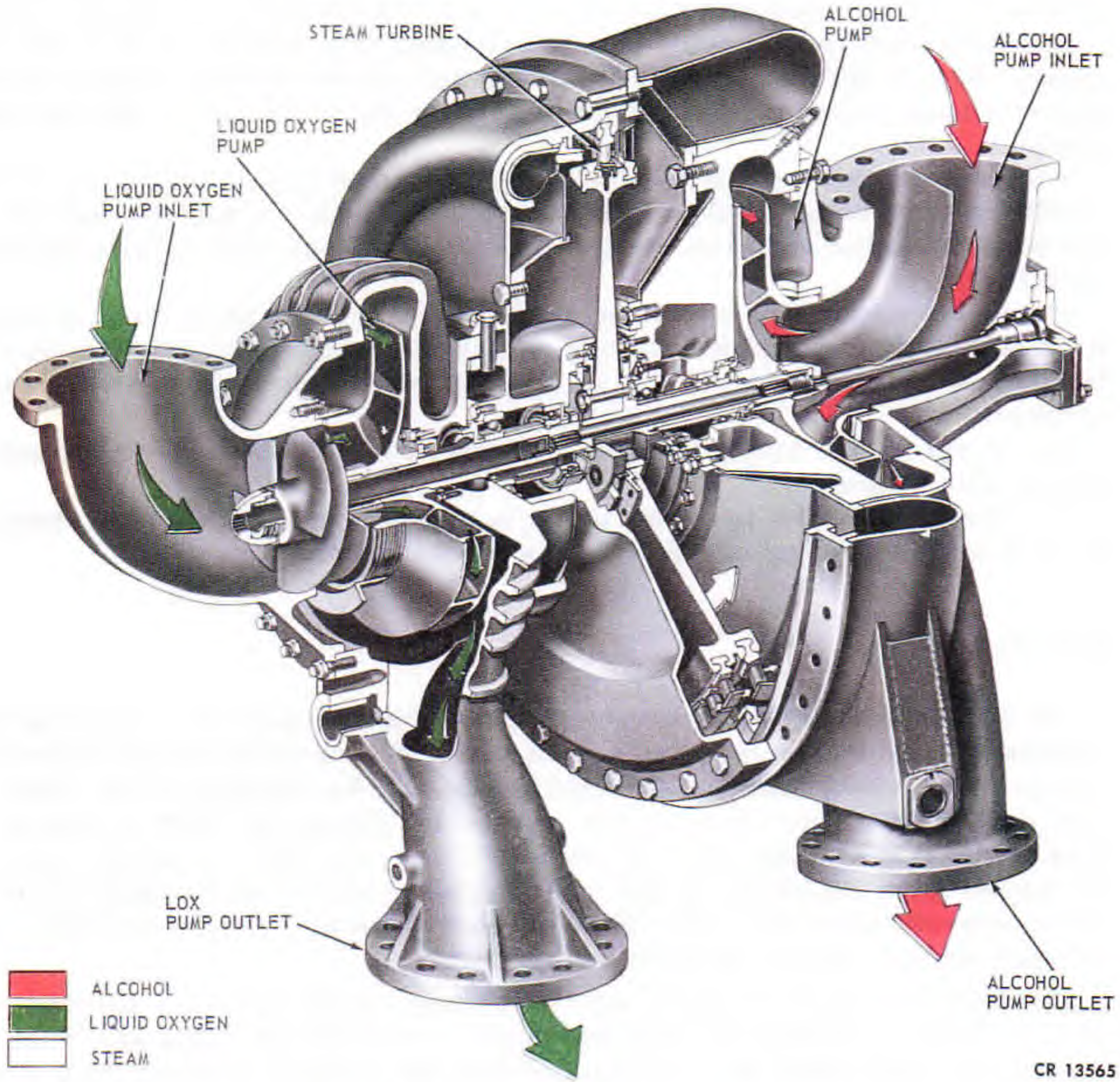


Figure V-4 – Operation of the Turbopump

The turbopump is the most critical item in the system. At the turbopump ambient temperatures of +700°F (steam) and -300°F (LOX) exist. Because of these extreme conditions, the turbopump must be well designed, even though it is in operation for only a short period of time.

PNEUMATIC SYSTEM

Engine starting and stopping must be controlled. The REDSTONE Missile uses a combination electro-pneumatic system to operate valves and to pressurize tanks.

An all-electrical system would require a bulkier, thus heavier, storage battery system and it would not assure reliable operation. An all-pneumatic system would require a large amount of tubing, which would make the system bulkier and more expensive.

A combination of the two has been found to be light, reliable, and inexpensive. Electrically operated solenoid valves are used to control the flow of high-pressure air to pressurize tanks and to operate the main fuel valve, oxidizer valve, and the peroxide shutoff valve.

The missile air supply is divided among three areas. The largest amount is stored in the section where the engine is located. This section supplies air to pressurize the fuel tank and the peroxide tank and to operate the main propellant valves and the shutoff valve.

The second largest amount is used to control the missile warhead and instrument section after separation.

The third supply is used to operate the air bearing system of the stabilized platform and to keep the instrument compartment at a constant pressure.

THRUST CONTROL

The thrust control system corrects for small thrust variations due to atmospheric conditions. This system makes use of the combustion chamber pressure to control thrust. (Thrust is a function of chamber pressure.) For example, if the chamber were designed to produce 75,000 pounds of thrust at 300 psig, the chamber would produce much less at 275 psig and much more at 325 psig. The only way the pressure can be changed in the REDSTONE system is by changing the quantity of propellants entering the chamber per unit time. Thus, if the chamber pressure is low, it is necessary to increase the flow rate of propellants into the chamber.

The thrust control system continuously monitors the chamber pressure and compares this pressure to a standard pressure preset into a thrust control amplifier. When the chamber pressure differs from the standard pressure, a signal is sent to the variable control valve in the steam system. This valve either increases or decreases the flow of peroxide to the steam generator which, in turn, increases or decreases steam flow.

As steam flow increases or decreases, the turbine speed also changes and, in turn, changes the speed of the turbopump. Changes in the speed of the turbopump cause the propellant flow rate to change which alters the chamber pressure and, hence, the thrust.

Low chamber pressure would cause a signal which would open the variable steam valve. This would increase the peroxide flow to the steam generator and increase the pump speed. More propellants per unit time would enter the chamber, bringing the chamber pressure up to the standard pressure set into the amplifier.

If the chamber pressure were too high, the system would decrease steam flow to slow the pumps and reduce the propellant flow rate. This would drop the chamber pressure, and, in turn, the thrust to the desired level.

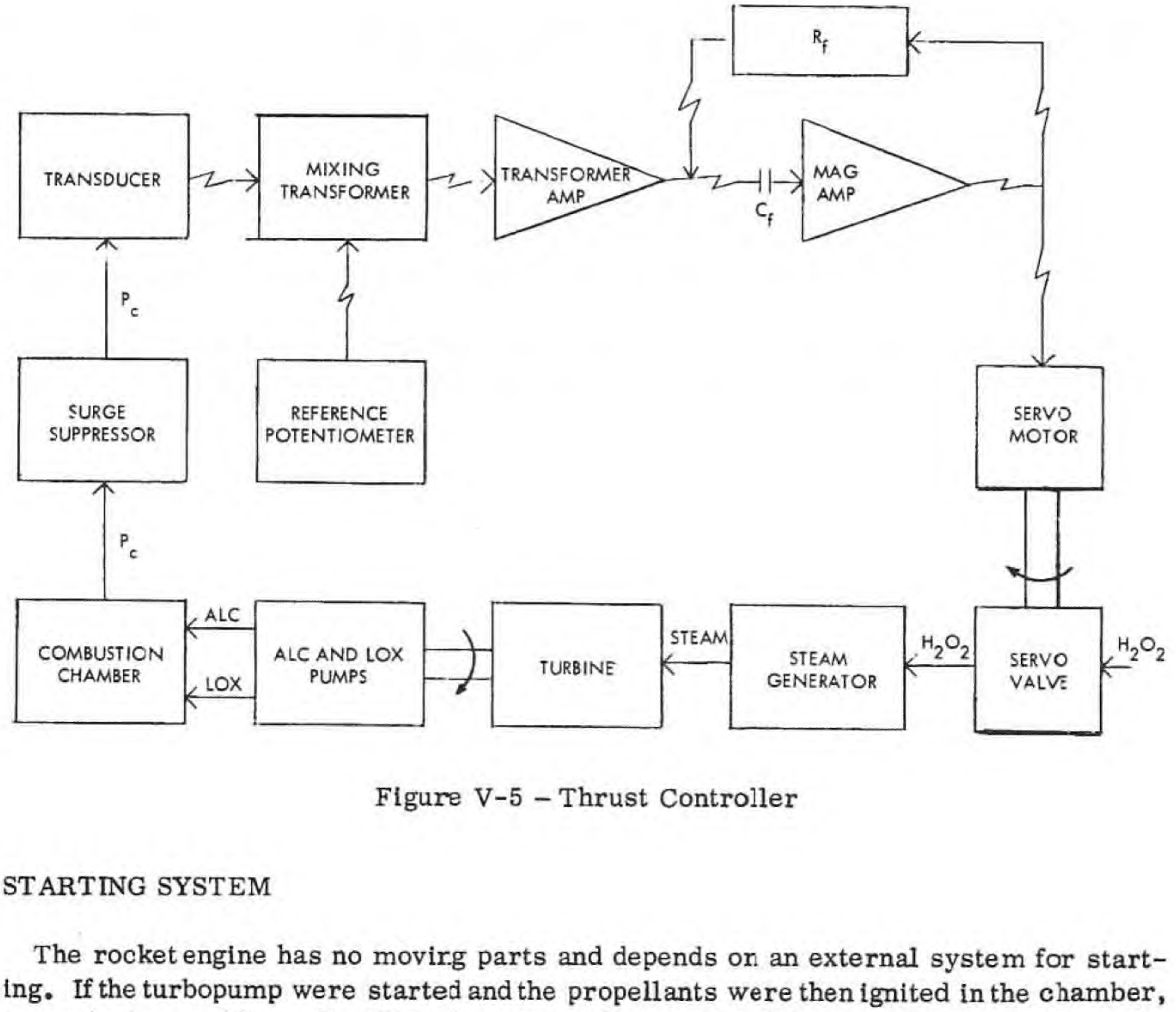


Figure V-5 – Thrust Controller

STARTING SYSTEM

The rocket engine has no moving parts and depends on an external system for starting. If the turbopump were started and the propellants were then ignited in the chamber, an explosion could result. Therefore, a small quantity of the propellants is sent to the chamber and ignited. The turbopump is then started, full thrust is obtained, and the missile is launched.

After all three tanks are pressurized, the pyrotechnic igniter in the injector is electrically fired. When this igniter fires, an electrical connection is broken, permitting the main oxidizer valve to open. This valve allows LOX to flow to the dome and through the injector and into the thrust chamber. When the oxidizer valve opens, it signals the solenoid that controlls the starting fuel to admit fuel through the passages in the injector to the ignition disc. This fuel mixes with the LOX flowing into the chamber and oxygen rich ignition occurs.

When the fire in the chamber becomes hot enough, another wire located beneath the exhaust nozzle is burned through, which signals the peroxide shutoff valve and main fuel valve to open. The opening of the fuel valve is slowed down by a restriction placed in the line to permit the turbopump a small amount of buildup time. As soon as the turbopump reaches operating speed (about 0.3 seconds) the engine is in mainstage operation (between 90 and 100 per cent of rated thrust) and flight begins.

CUTOFF

When the missile has been in flight for a predetermined period of time, the guidance system sends a signal to the engine to shut down.

This is accomplished by first closing the peroxide shutoff valve and then closing the fuel and ozidizer valves.

The engine and tanks are no longer needed and are separated a short time later from the body unit. The thrust unit falls about ten miles short of the target.

CHAPTER VI

PROPELLANT SYSTEMS

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CHAPTER VI PROPELLANT SYSTEMS

GENERAL

A propellant may be defined as a solid, liquid, or gaseous material or various combinations of these materials whose heat of combustion is utilized to propel a missile.

In the selection of a propellant several factors, properties, and characteristics, including the following, must be considered:

Total impulse in lb-sec (I_T) = thrust in pounds (T) × duration in seconds (t). This is used in rating or comparing various propellants.

$$\text{Specific impulse in lb-sec/lb } (I_{sp}) = \frac{\text{total impulse in lb-sec } (I_T)}{\text{weight of solid in lbs } (W)}$$

This is used in rating or comparing solid propellants.

$$\text{Specific thrust in lb/lb/sec } (T_{sp}) = \frac{\text{thrust in lb } (T)}{\text{weight rate of flow in lb per sec } (\dot{W})}$$

This is a common method of comparing liquid propellants.

Density of a propellant is an important factor. A given weight of a dense propellant can be carried in smaller lighter tanks than the same weight of a lower density propellant. Liquid hydrogen, for example is high in energy and its combustion gases are light. However, it is a very bulky substance and requires large tanks. The dead weight of these tanks partially offsets the high specific impulse of the hydrogen propellant.

In engine operation, problems are sometimes created by chemicals that yield an excellent specific impulse. For example:

(a) Can the propellant be used adequately as a coolant for the hot thrust-chamber wall?

(b) Is the propellant sufficiently stable so that it can be safely stored and handled?

Most propellants are corrosive, flammable, and/or toxic. A propellant that gives good performance is usually a highly active chemical. Many propellants are highly toxic, to a greater degree even than most war gases. Some propellants are so corrosive that only a few special materials can be used to contain them. Some propellants burn spontaneously upon contact with air or upon contact with an organic substance, or in certain cases, upon contacting most common metals.

Since some propellants are used in very large quantities, the availability of raw materials must be considered. Also, in some cases, an entire new chemical plant must be built in order to obtain adequate amounts of a propellant.

In the chemical-type rocket engine two general types of propellants are used; the liquid propellant and the solid propellant.

Two general types of the solid propellant are in use: the double-base propellant and the composite type. The double-base propellant consists of nitrocellulose and nitroglycerine, plus additives in small quantities. There is no separate fuel and oxidizer. Extrusion methods are usually employed in the manufacture of this type of solid propellant. However, casting has been employed.

The composite type of solid propellant uses separate fuel and oxidizer which are intimately mixed in the solid grain. The oxidizer is usually ammonium nitrate, potassium chlorate, or ammonium chlorate and often comprises as much as four-fifths or more of the whole propellant mix. The fuels used are hydrocarbons, such as asphaltic-type compounds, or plastics.

Solid propellants offer the advantage of minimum maintenance and instant readiness. However, the solids usually require carefully controlled storage conditions and offer handling problems, particularly in the very large sizes. Protection from mechanical shocks or abrupt temperature changes that may crack the grain is essential.

Liquid propellants are divided into three general classes: Fuels, oxidizers, and monopropellants. Theoretically, the most effective fuel component is hydrogen, and the most effective oxidizing agents are fluorine or ozone.

Liquid ammonia, the alcohols, aniline mixtures, hydrazines, hydrogen, and various petroleum products and derivatives are used or are theoretically possible to use as propellants.

In the class of oxidizers, the following are used or considered for use: LOX, fuming nitric acids, fluorine, chlorine trifluoride, ozone, ozone-oxygen mixtures, and concentrated hydrogen peroxide.

Ethylene oxide, hydrazine, hydrogen peroxide, and nitromethane are monopropellants. It follows that hydrazine and hydrogen peroxide may be utilized as a fuel and oxidizer, respectively, as well as a monopropellant.

Certain propellant combinations are hypergolic; that is, they ignite spontaneously upon contact of the fuel and oxidizer. Others require an igniter to start burning, although they will continue to burn when injected into the flame of the combustion chamber.

In general, the liquid propellants in common use yield specific impulses superior to those of available solids. On the other hand, they require more complex propulsion systems to transfer the liquid propellants to the combustion chamber.

Certain unstable liquid chemicals, which under proper conditions will decompose and release energy, have been tried as rocket propellants. Their performance, however, is inferior to that of bipropellants and they are of interest only in specialized applications.

Outstanding examples of this type of propellant are hydrogen peroxide and ethylene oxide. Occasionally, a separate propellant is used to operate the gas generator which supplies the gas to drive the turbopumps of liquid rockets.

Table VI-I – SPECIFIC IMPULSE OF SOME TYPICAL CHEMICAL PROPELLANTS

Propellant combinations:	Isp range (sec)
Monopropellants (liquid):	
Low-energy monopropellants	160 to 190.
Hydrazine	
Ethylene oxide	
Hydrogen peroxide	
High-energy monopropellants:	
Nitromethane	190 to 230.
Bipropellants (liquid):	
Low-energy bipropellants	200 to 230.
Perchloryl fluoride – Available fuel	
Analine – Acid	
JP-4 – Acid	
Hydrogen peroxide – JP-4	
Medium-energy bipropellants	230 to 260.
Hydrazine – Acid	
Ammonia – Nitrogen tetroxide	
High-energy bipropellants	250 to 270.
Liquid oxygen – JP-4	
Liquid oxygen – Alcohol	
Hydrazine – Chlorine trifluoride	
Very high-energy bipropellants	270 to 330.
Liquid oxygen and fluorine – JP-4	
Liquid oxygen and ozone – JP-4	
Liquid oxygen – Hydrazine	
Super high-energy bipropellants	300 to 385.
Fluorine – Hydrogen	
Fluorine – Ammonia	
Ozone – Hydrogen	
Fluorine – Diborane	
Oxidizer-binder combinations (solid):	
Potassium perchlorate:	
Thiokol or asphalt	170 to 210.
Ammonium perchlorate:	
Thiokol	170 to 210.
Rubber	170 to 210.
Polyurethane	210 to 250.
Nitropolymer	210 to 250.

Table VI-I – SPECIFIC IMPULSE OF SOME TYPICAL CHEMICAL PROPELLANTS (Continued)

Propellant combinations:	Isp range (sec)
Oxidizer-binder combinations (solid): (continued)	
Ammonium nitrate:	
Polyester	170 to 210.
Rubber.	170 to 210.
Nitropolymer	210 to 250.
Double base	170 to 250.
Boron metal components and oxidant	200 to 250.
Lithium metal components and oxidant	200 to 250.
Aluminum metal components and oxidant.	200 to 250.
Magnesium metal components and oxidant	200 to 250.
Perfluoro-type propellants	250 and above.

OXIDIZER SYSTEM

Characteristics and Properties of Oxygen

Oxygen may exist as a solid, liquid, or gas. These states are determined by the temperatures and pressures under which it is handled. Oxygen may be liquefied if cooled below a temperature of -297.35°F at atmospheric pressure. By increasing the pressure, oxygen may exist as a liquid at temperatures above -297°F. The critical temperature of oxygen is -182°F, it will not remain a liquid above this temperature regardless of the pressure applied.

Symbol – O, formula – O_2

Atomic weight – 16

Valence – 2

Concentration in air – 20.99% sea level

Color of LOX – pale blue

Viscosity (LOX) – nonviscous (water-like fluid)

Normal freezing point – (-219°C) (-362°F) sea level

Normal boiling point – (183°C) (-297°F) sea level

Critical temperature – (-119°C) (-182°F) sea level

Critical pressure – 47.7 atmospheres (730.6 psi)

Density:

Gas – 0.08305 lb/cu ft
Liquid – 71.5 lb/cu ft, 9.69 lb/gal

Gaseous oxygen is approximately 1.103 times heavier than air.

LOX is approximately 1.14 times heavier than water.

Gas constant R = 48.31 ft-lb/lb °R

Specific Heat – 0.4 Btu/lb/°F

Heat of Vaporization – 92 Btu/lb

Surface Tension – 18.3 dynes/cm

LOX is insoluble with all common solvents, since it freezes them on contact.

In its gaseous state it is a strong oxidizing agent.

The extreme cold temperature of LOX tends to make metals, plastics, rubber, and most other materials very brittle.

Oxygen is nontoxic.

Specification – Type II, Grade "A" of MIL-O-8069

LOX is an explosive hazard if subject to shock or ignition when contaminated with organic materials such as oil, grease, carbon black, paper, wood, cork, gasoline, JP fuels, kerosene, and metal in the form of powder or shavings.

In the absence of organic contamination LOX is considered stable and its vapors create no particular hazard. However, it supports combustion when in the vicinity of, or enclosed with, combustible material.

LOX is always -182°F or lower in temperature (depending on pressure), is pale blue in color, and flows like water. Under no condition should it be restricted in a given space. For example, one cubic foot of LOX represents over 800 cubic feet of gaseous oxygen at atmospheric pressure and would build up to approximately 112,000 psi if confined to the original cubic foot of space.

LOX is dangerous, and there are a few rules that must be followed to assure against accidents. Possible danger is based on three general characteristics of LOX:

The rate of combustion of most materials can be greatly increased by the presence of pure oxygen.

Human contact with LOX or uninsulated lines at a temperature of -297°F can result in severe frostbite. Some types of material and equipment vulnerable to freezing conditions can be damaged easily.

LOX, if confined, will eventually evaporate and build up a tremendous pressure which will result in the rupture of the tank in which it is stored.

The ground equipment used in the oxidizer system consists of LOX generating and production equipment, a storage container, transportation vehicles, and transfer equipment.

The Engineering Company is equipped with the LOX generating facilities (an air supply semitrailer and an air separation semitrailer). The air supply semitrailer contains the compressed air supply assembly powerplant which is powered by four diesel engines, each of which drives four 4-stage air compressors.

The air separation semitrailer contains the oxygen-nitrogen separation assembly, which consists of the heat exchangers, air dryers, refrigeration system distillation column, carbon dioxide filters, and an electric generator. Both semitrailers are towed by standard M-52 truck tractors.

LOX from the generating plant is stored in tanks that have a capacity of 70,000 pounds each. The storage tank is basically a large thermos bottle; that is, it has double wall (inner and outer tank) with a vacuum-insulated space between. It is skid mounted and complete with pump, valves, switches, indicators, and controls for transfer of LOX. The storage tanks are equipped with safety valves and rupture disks for protection against excessive internal pressure.

LOX from the storage tanks is transported and stored at the launch site in two 9-ton, tank-type semitrailers towed by standard M-52 truck tractors. The transporters are similar in construction to the storage tank. The offset design of two different diameters gives optimum weight distribution and provides a low center of gravity with a fifth wheel. A compartment at the rear of the trailer houses the transfer equipment necessary to transfer LOX to the missile tank at rates up to 150 gpm against head pressures up to 75 psi.

The main LOX components of the REDSTONE missile system are: the LOX fill and drain valve, the LOX container or tank, the LOX pump, the main LOX valve, the LOX dome, the injector and the combustion chamber. Since LOX evaporates (boils off), it is necessary to replace this loss by means of a replenishing valve. Also, excessive pressure buildup is vented to the atmosphere by means of a vent valve. Miscellaneous equipment includes such items as a transfer hose, a "Y" connector, a fueling ladder, couplings, and other materiel.

Because of size, weight, and structural considerations, propellants are transferred to the missile only when the missile is in the vertical position.

Filling Procedure

LOX is delivered to the firing site by the two 9-ton semitrailers and positioned near the missile. The trailers are connected to the missile fill and drain port by means of hoses, the "Y" connector, the fueling ladder, and other equipment. After the hookup is completed, precooling of the lines and pumps is started by a gradual flow of LOX

through the delivery system. When precooling has been accomplished, the pumps are activated and the transfer of LOX is accomplished. One semitrailer starts the pumping operation first, and after an interval of three or four minutes, the second semitrailer commences to pump. This procedure assures that a sufficient amount of LOX will be reserved in the second semitrailer for replenishing.

When the filling operation (filling weight is 25,430 pounds) has been completed, hoses and accessories are disconnected and secured. One semitrailer is withdrawn from the site while the trailer with the reserve supply of LOX moves to the replenishing position (150 feet from the missile). A replenishing line is installed, and the LOX is topped into the missile tank at regular intervals to replenish the loss from evaporation until the missile fire command is given.

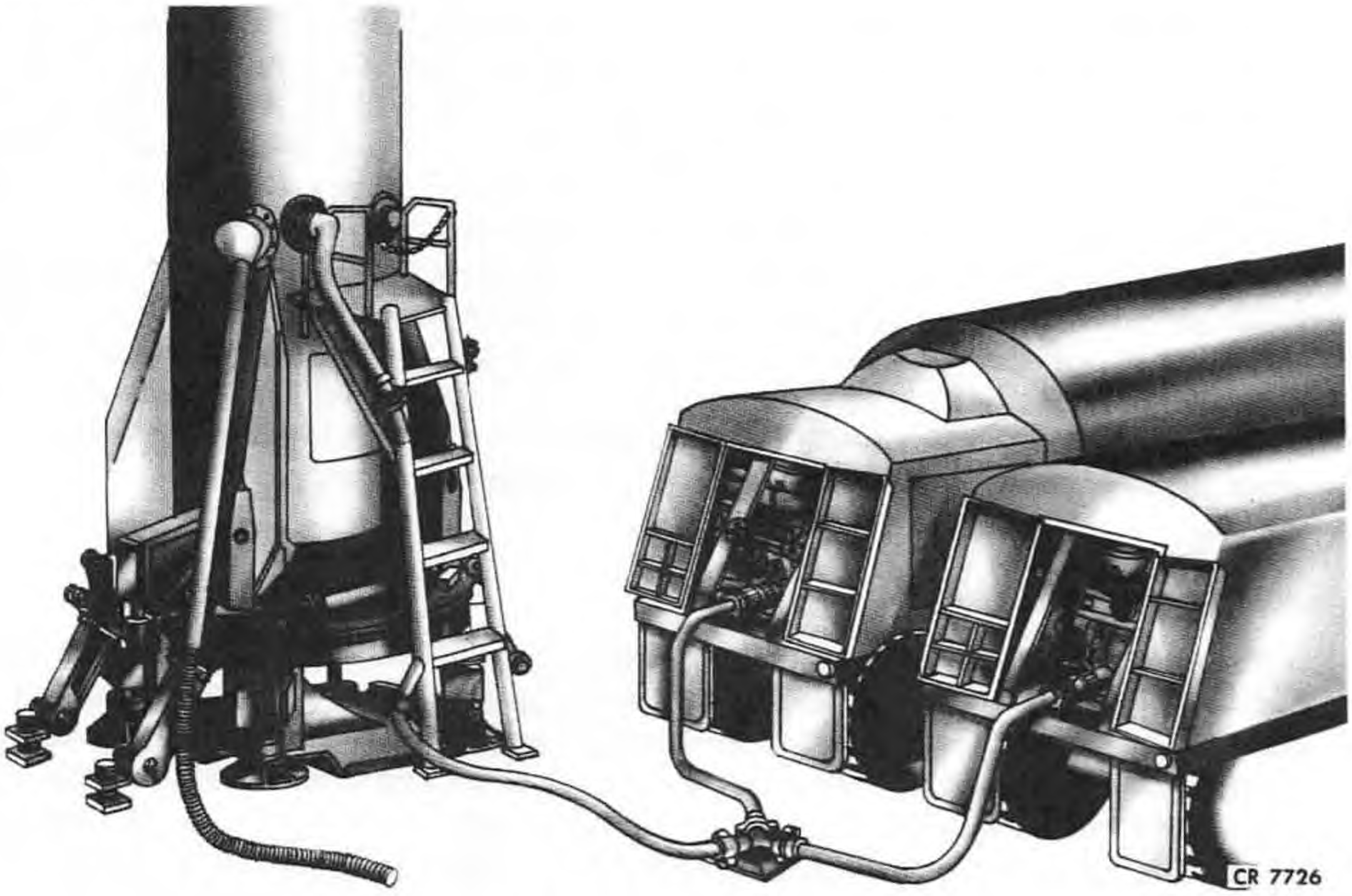

Figure VI-1 – LOX Filling

FUEL SYSTEM

The REDSTONE Missile uses a denatured ethyl alcohol and water mixture (75 per cent alcohol, 25 per cent water) as a fuel. This fuel is mixed with LOX (oxidizer) in the thrust chamber and burned to produce thrust for propelling the missile.

Ethyl alcohol (C_2H_5OH), or grain alcohol, is a colorless, chemically stable, flammable liquid. It has a characteristic odor and is not sensitive to shock. Ethyl alcohol is relatively inert and does not react to any great extent with the metal of valves, piping, or tanks. Other properties of ethyl alcohol are:

Boiling point (°C)	78.4
Flash point (°C, enclosed)	12
Auto-ignition temperature (°C)	426
Specific gravity at 20/4°C	0.789
Vapor density	1.59
Vapor pressure at 25°C (mm Hg)	50

The alcohol is shipped and stored in 55-gallon (expendable) steel drums. The alcohol is transferred from the drums to the alcohol semitrailer, the basic function of which is to transport alcohol and inert fluid to the firing site and to pump alcohol and inert fluid into the REDSTONE Missile fuel system. The 3,000-gallon, 2-wheel, XM388 alcohol semitrailer consists of a 3,000-gallon aluminum tank, and a pumping compartment which contains a 20-gallon stainless-steel tank (for inert lead fluid) and two pumping units. The semitrailer is mounted on a single-axle chassis.

The alcohol tank is an elliptically-shaped, one-compartment tank with a capacity of 3,000 gallons plus 3 per cent expansion. A 1-inch-thick rubber insulation covers the entire tank, with the exception of the pumping compartment. The insulation helps to keep the alcohol at the proper temperature. The tank contains the necessary vents, fusible plugs, a manhole and fill cover assembly, a capacity indicator, a strainer, and other items necessary for the safety and operation of the tank.

Fuel Transfer System

The primary function of the fuel transfer system is to deliver strained and metered fuel to the missile. The system is designed to perform a variety of associated fueling operations including: evacuating the fueling hose, filling the semitrailer tank from alcohol drums, mixing or recirculating the tank contents, and servicing the missile with fuel from an outside source. It is also capable of pumping into the semitrailer from an outside source through the gravity drain valve, pumping out of the semitrailer through the meter bypass, draining into or out of the semitrailer gravity drain valve, draining by gravity flow from the missile back to the semitrailer tank, and pumping from the missile into the semitrailer through the eductor system. The transfer equipment consists of a centrifugal pump coupled to an explosion-proof motor, a fuel metering chamber and register, gages and instruments, and other valves and associated piping used to direct the fuel flow.

The fuel transfer pump is mounted on the end of the motor shaft and is designed to deliver 250 gpm at a static head of 43 feet. The pump is a centrifugal, non-self-priming type and is equipped with a mechanical seal. The motor is rated at 15 hp at 3000 rpm and operates on 208-volt, 60-cps, 3-phase power.

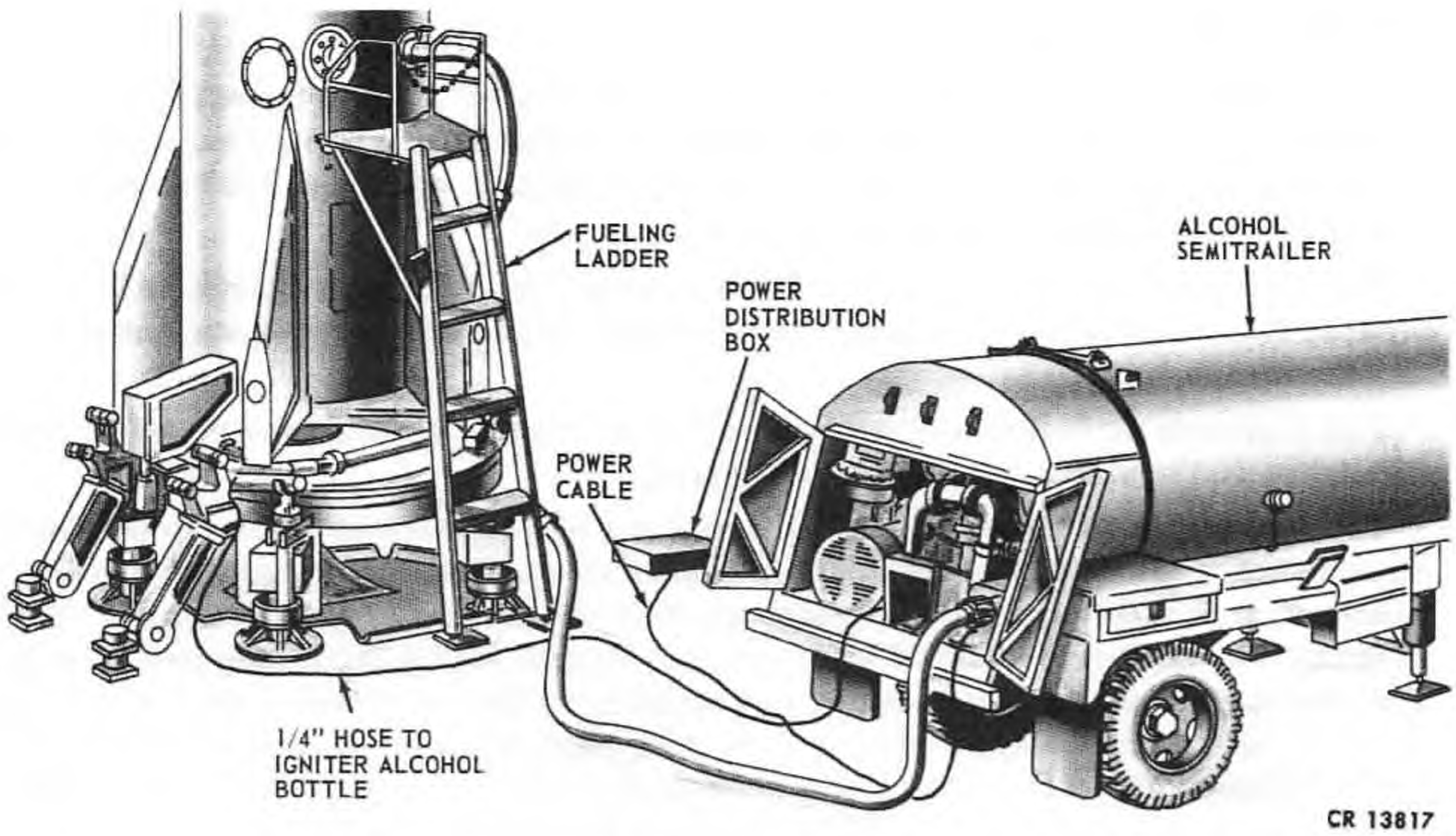

Figure VI-2 – Alcohol Fueling

The metering system consists of the meter register, the auto-stop valve, the metering chamber, and the air release and strainer. The purpose of the system is to accurately record the amount of fuel being pumped into the missile.

Other equipment such as gages, instruments, valves, and associated piping are used to control and direct the fuel flow but these items are considered to be standard equipment.

Tank Heater System

The tank heater system is designed to heat the alcohol-water fuel solution prior to fueling the missile. Initial heating takes place in the support area. Any additional heating required to maintain the prescribed fuel temperature would take place at the firing site while the alcohol semitrailer is in standby position. In some cases, the entire heating operation may be performed at the firing site. Circumstances will dictate the procedure used, and the final choice is the prerogative of the firing command.

The heater system is electrically powered by a 208-volt, 3-phase, 60-cps supply received from an external power source. The system consists of twelve 4.5-kilowatt immersion-type electrical heating elements, six on each side of tank; two magnetic starters, located in the heater distribution box; four thermostats, two on each side of the tank; two safety systems; and an indicator light unit located in the rear of the pump compartment.

Inert Fluid Transfer System

The function of the inert fluid system is to deliver inert fluid to the missile.

The inert fluid transfer equipment consists of a centrifugal pump and explosion-proof motor mounted on a common shaft, a stainless-steel tank, strainers and valves, a hose reel, and other plumbing necessary to direct the flow.

The inert fluid tank is a stainless-steel, rectangular, single-compartment tank with a capacity of 20 gallons. It is suspended from the top of the pump compartment by three aluminum straps.

The seal-less inert fluid pump is on a common shaft with the explosion-proof motor and delivers 5 gpm at a minimum 40-foot head.

The semitrailer arrives at the firing site along with the various other ground support equipment. The alcohol semitrailer remains in standby status until after vertical checkout of the missile. Preparations are then made for fueling the missile. These preparations consist of: installing the missile fueling ladder, installing fueling valves and hoses, emplacing the air heater, and providing a lithium chloride lead start which consists of pumping lithium chloride into that portion of the missile alcohol system below the main alcohol valve in order to provide smoother ignition when the missile is fired. Fueling is then begun. After fueling the missile, the alcohol semitrailer is moved out of the firing area.

The main items of the missile fuel system are: the alcohol fill and drain valve, the alcohol tank, the pump, main alcohol valves, the injector, the combustion chamber, and other associated components such as the vent valve, the pressurizing valve, check valves, piping, and couplings.

The alcohol tank, which makes up the forward portion of the missile center section, is filled and drained through the mechanically actuated alcohol tank fill and drain valve. This valve is mounted on the missile skin near the aft bulkhead of the center section and is connected to the main alcohol supply ducting by an expansion joint. The valve is composed of a cast aluminum-alloy body, an O-ring type seat which is spring-loaded to the normally closed position, a seat ring, and an adapter flange.

The alcohol pump forces the flow of alcohol from the alcohol tank to the rocket engine combustion chamber at a delivery pressure of 420 psi. The fuel pump and turbine are coupled to, and driven by, a common shaft. The alcohol pump is of the single-entry, centrifugal type, utilizing radial flow impellers. The impellers incorporate balance ribs on the inboard side to facilitate hydraulic balancing of end thrust by the adjustment of rib-to-housing clearances. The alcohol pump has a nominal delivery of 1333 gpm.

The main alcohol valve controls the flow of fuel to the rocket engine combustion chamber. It is actuated pneumatically by a four-way solenoid valve. The valve is installed between the thrust chamber alcohol manifold and the alcohol ducts.

The injector disperses alcohol into the rocket engine combustion chamber in small streams and mixes with like streams of LOX also introduced by the injector.

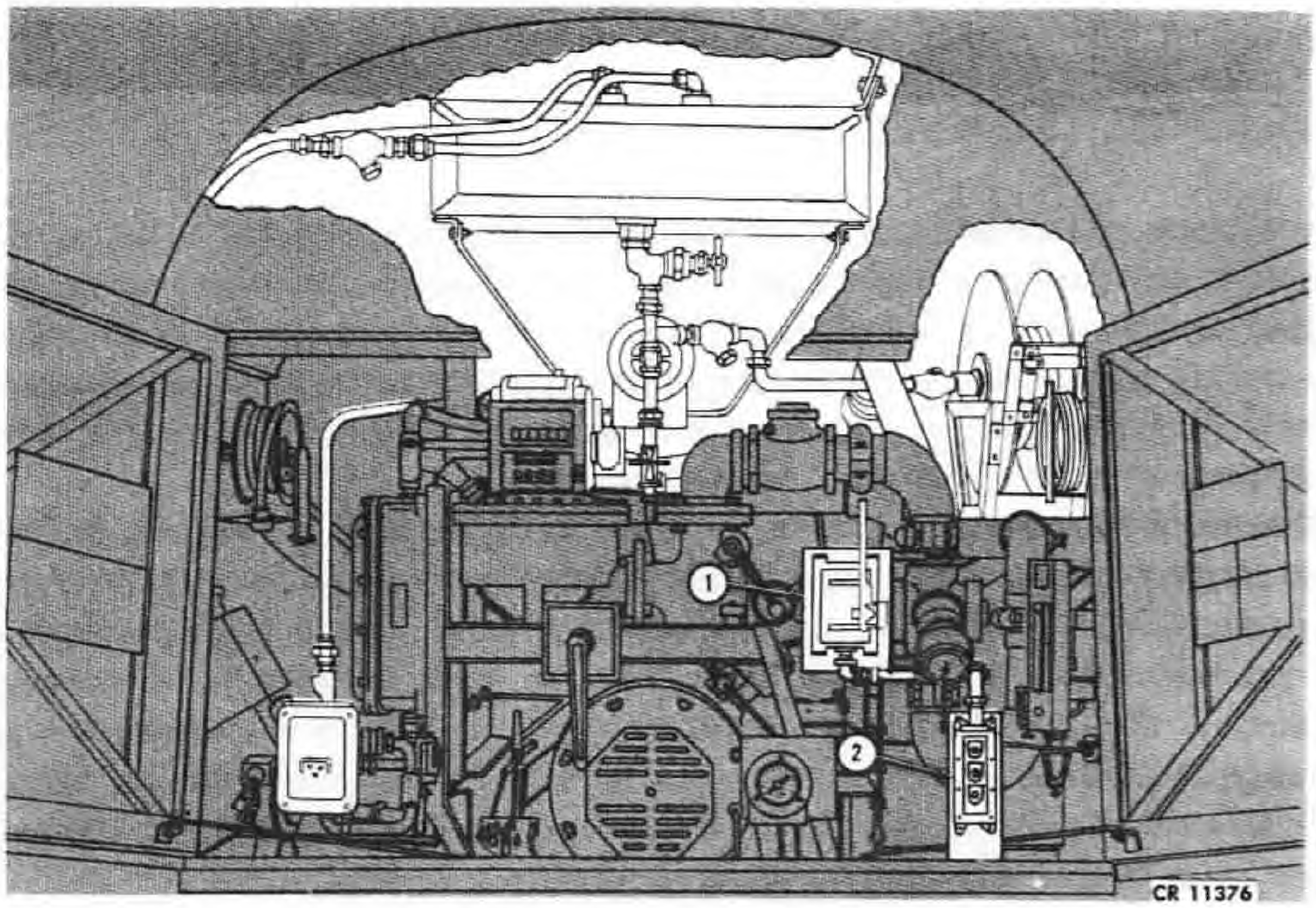

Figure VI-3 – Inert Fluid System

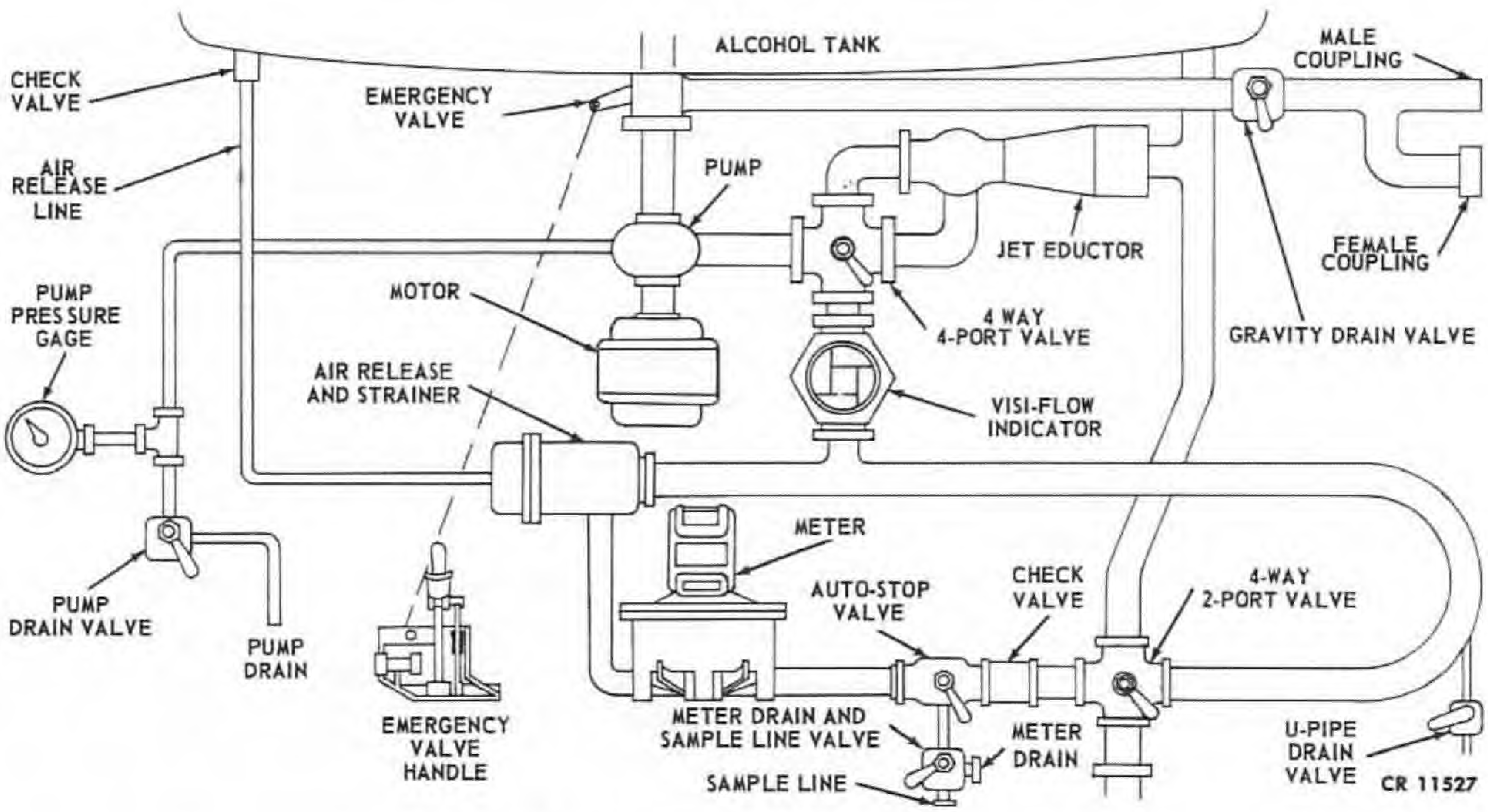

Figure VI-4 – Fuel Transfer System

HYDROGEN PEROXIDE SYSTEM

The hydrogen peroxide system provides the power for operating the turbopump assembly that delivers propellants to the rocket engine combustion chamber.

Hydrogen peroxide is a colorless liquid. In the pure state, it is extremely stable; however, any impurities introduced during manufacture, shipment, storage, or handling will reduce this stability. Metals such as iron, copper, chromium, and their salts, will decompose hydrogen peroxide on contact.

Hydrogen peroxide itself is nonflammable. However, it is a strong oxidizer and, if allowed to remain in contact with readily oxidizable organic materials, may cause spontaneous combustion. In addition, hydrogen peroxide solutions are catalytically decomposed by many metals and their salts, ordinary dirt, ferments, enzymes, and other substances. This decomposition liberates oxygen, which will promote the combustion of flammable materials. Concentrated solutions are powerful oxidizing agents that can rust iron and steel. These solutions can furnish oxygen and heat to burn combustibles such as wood, leather, paper, cotton, and wool.

All materials which must come into contact with concentrated hydrogen peroxide are chosen very carefully. Storage tanks and pipe lines should be made of 99.6 per cent or 2S aluminum. Pipe should be bent and flange welded to avoid objectionable screw-on fittings. Gate valves are recommended and should contain 99.6 per cent aluminum, 2S, or 43S alloy. Pumps should be made of 43S aluminum or type 316 stainless steel. All tanks and containers must be treated by a special pickling procedure before use. During all operations, the prescribed protective clothing is worn.

Hydrogen peroxide is received and stored in special 86-gallon drums, which are transported to the firing site by the hydrogen peroxide truck. The hydrogen peroxide truck also supplies hydrogen peroxide to the missile by means of a pump, hoses, and other equipment. The truck is a modified 3/4-ton M-37 cargo truck. The modifications to the truck include a monorail system, an electrically operated pumping unit, an overflow tank, and the necessary fittings, hoses and cables.

The monorail assembly consists of an I-beam welded to, and supported by, two A-frames which are bolted to the sides of the truck. The purpose of the monorail assembly is to provide a support for the chainfall assembly when it is used to handle the drum. The monorail extends beyond the end of the truck to allow the hydrogen peroxide drum to be lifted from the ground. The chainfall assembly is used to raise and lower the drum and to traverse the length of the monorail.

There are three cover assemblies used with the hydrogen peroxide drum: the lower collection ring cover assembly, the upper collection ring cover assembly, and the drum cover assembly. The cover assemblies provide insulation and air space around the drim to aid in maintaining the hydrogen peroxide at the prescribed temperature (65°F to 85°F). The air space allows for the circulation of hot air (for heating) or gaseous nitrogen (for cooling). A heater assembly, in conjunction with the cooling system, regulates the temperature of the hydrogen peroxide.

The hydrogen peroxide pump is a rotary, positive-displacement type, capable of delivering 8 gpm; the pump serves two functions in the missile system: 1) to pump hydrogen peroxide from the drum into the missile, and 2) to recirculate hydrogen peroxide through the drum for even temperature distribution.

An overflow tank assembly (6-gallon capacity) is used to catch the overflow of hydrogen peroxide from the missile during missile loading operations.

After servicing, all equipment except the overflow tank and hose is returned to the hydrogen peroxide truck, which then moves to a safe distance from the firing site. The overflow tank and hose are moved from the firing site at a specified time just prior to missile firing.

The main components of the missile peroxide system are: the fill and drain valve, the tank, the thrust control servo valve, the main peroxide valve, the vent and overflow valve, the control valve, and the steam generator.

The hydrogen peroxide tank, which is mounted to the thrust frame at the forward end of the rocket engine, is filled and drained through the mechanically actuated peroxide fill and drain valve. The tank has a capacity of 75 gallons.

The main peroxide valve is a pneumatically operated, poppet-type valve that is spring loaded to a normally closed position.

The steam generator is a steel body and cover assembly which is copper-coated and nickel-plated to resist corrosion. The generator is mounted on the steam inlet manifold of the turbopump and contains a pellet-type decomposition catalyst (potassium permanganate). Hydrogen peroxide, which enters the top of the generator under supply tank pressure, is sprayed by the injector through the diffuser plate and into the catalyst, where it decomposes into steam. The steam is then directed from the bottom of the generator into the turbopump manifold.

The electrically operated, gate-type, thrust control servo valve, installed in the peroxide supply line upstream of the main peroxide valve, controls motor chamber pressure by automatically throttling the peroxide flow to the steam generator. The reduction in peroxide flow regulates the pumping rate of the turbopump.

After passing through the steam turbine, the steam enters an exhaust duct which directs it through the heat exchanger. The steam heats the coils in the heat exchanger and then passes overboard through the exhaust duct.

The pumping system recirculates hydrogen peroxide prior to servicing the missile, and pumps hydrogen peroxide into the missile.

All the hydrogen peroxide in the drum must be at the same temperature before it is pumped into the missile. The purpose of recirculation is to mix the hydrogen peroxide and thereby maintain a consistent temperature in the drum.

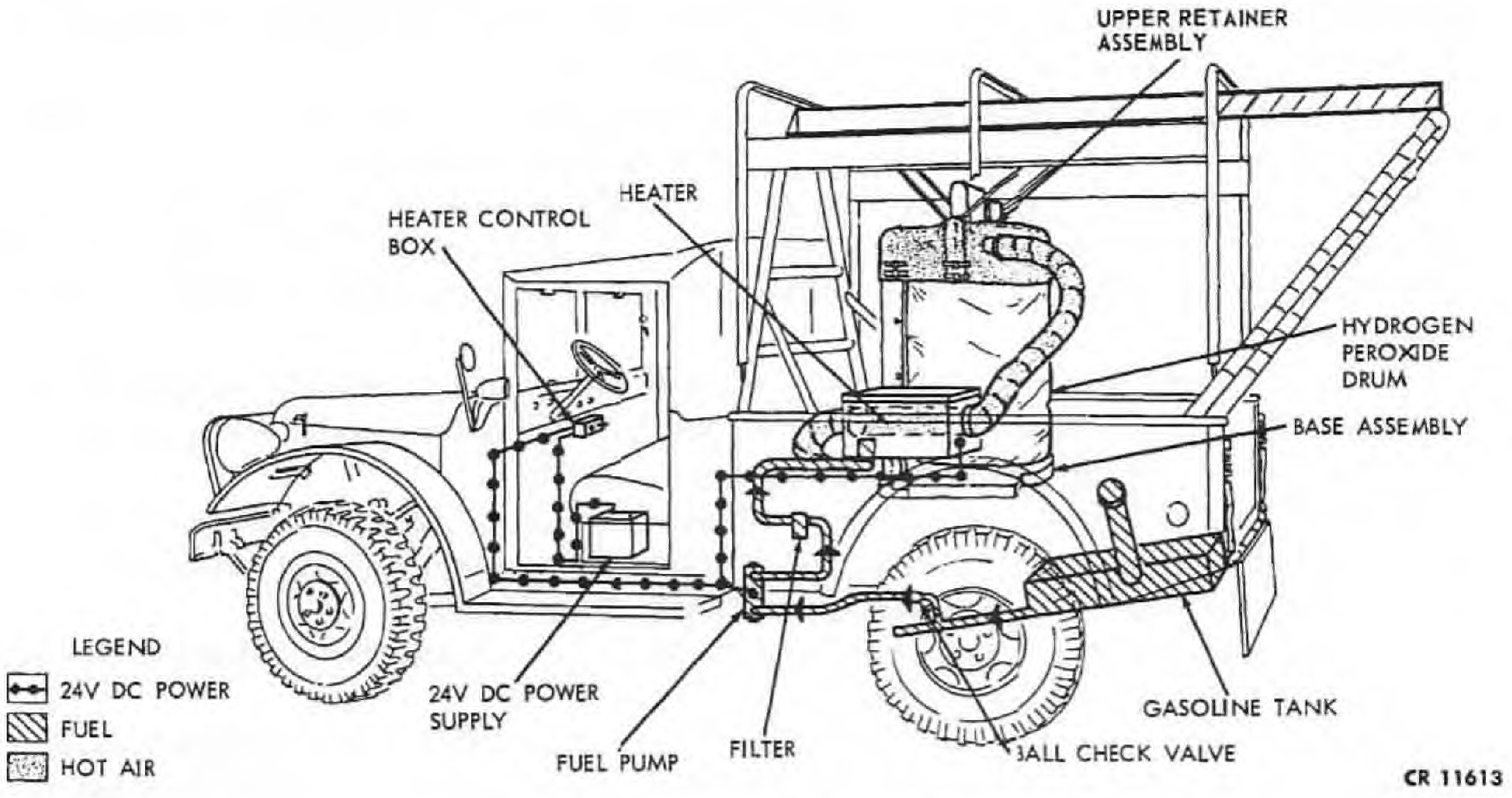

Figure VI-5 – Drum Heating System

OUTPUT
ON-HI . . . . 30,000 BTU/hr
ON-LO . . . . 12,000 BTU/hr

VOLTAGE REQUIRED
Maximum. . . . . 28 vdc
Minimum . . . . 18 vdc

FUEL any grade gasoline

CURRENT CONSUMPTION
Starting . . . . 14 amperes
Operating. . . . . 7 amperes

FUEL CONSUMPTION
Maximum. . . . . 0.44 gph
Minimum . . . . 0.20 gph

TYPE OF FUEL
PUMP . . . . electric

SOURCE OF FUEL . . . gas tank of servicer

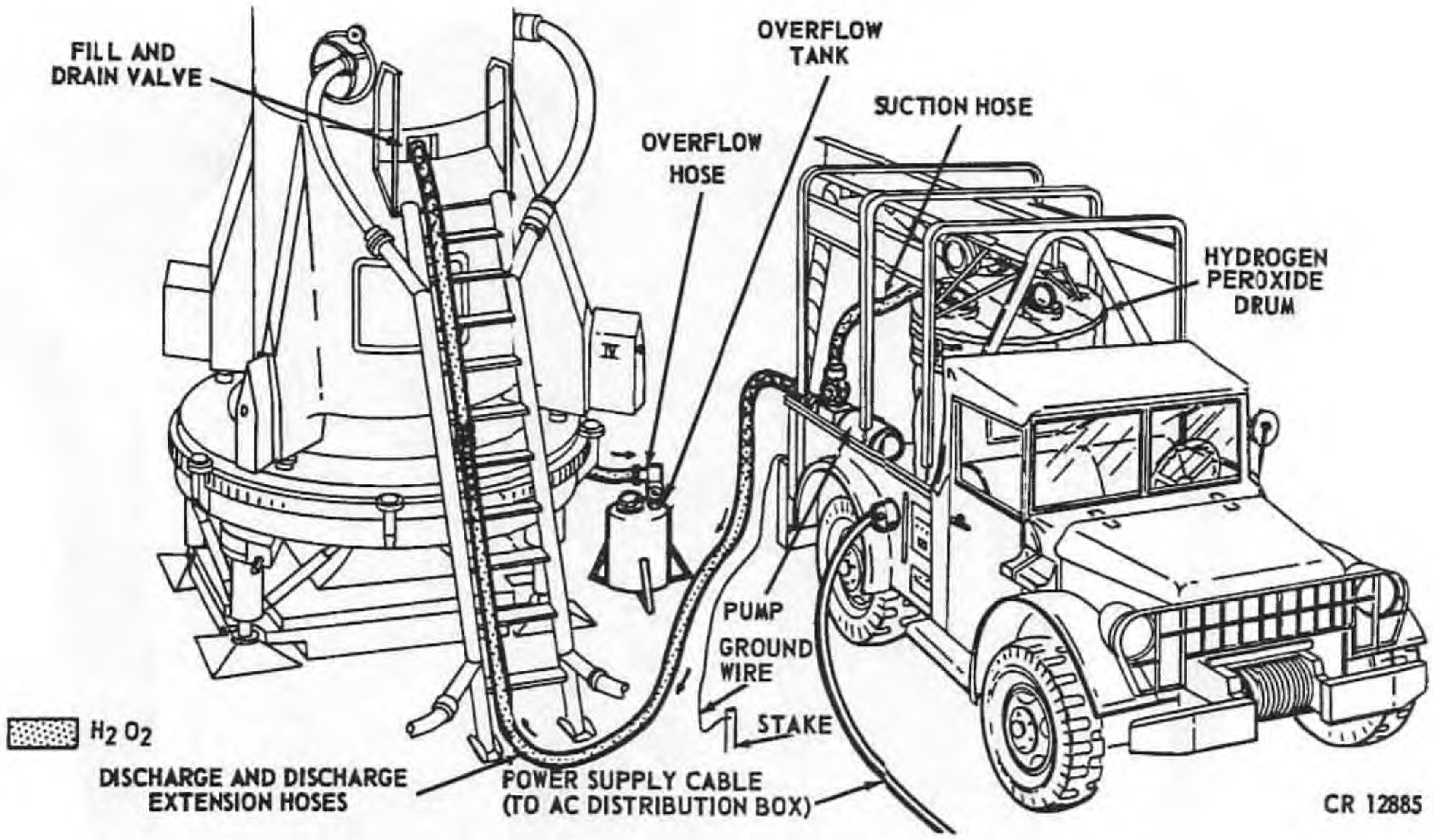

Figure VI-6 – Hydrogen Peroxide Servicing of the Missile

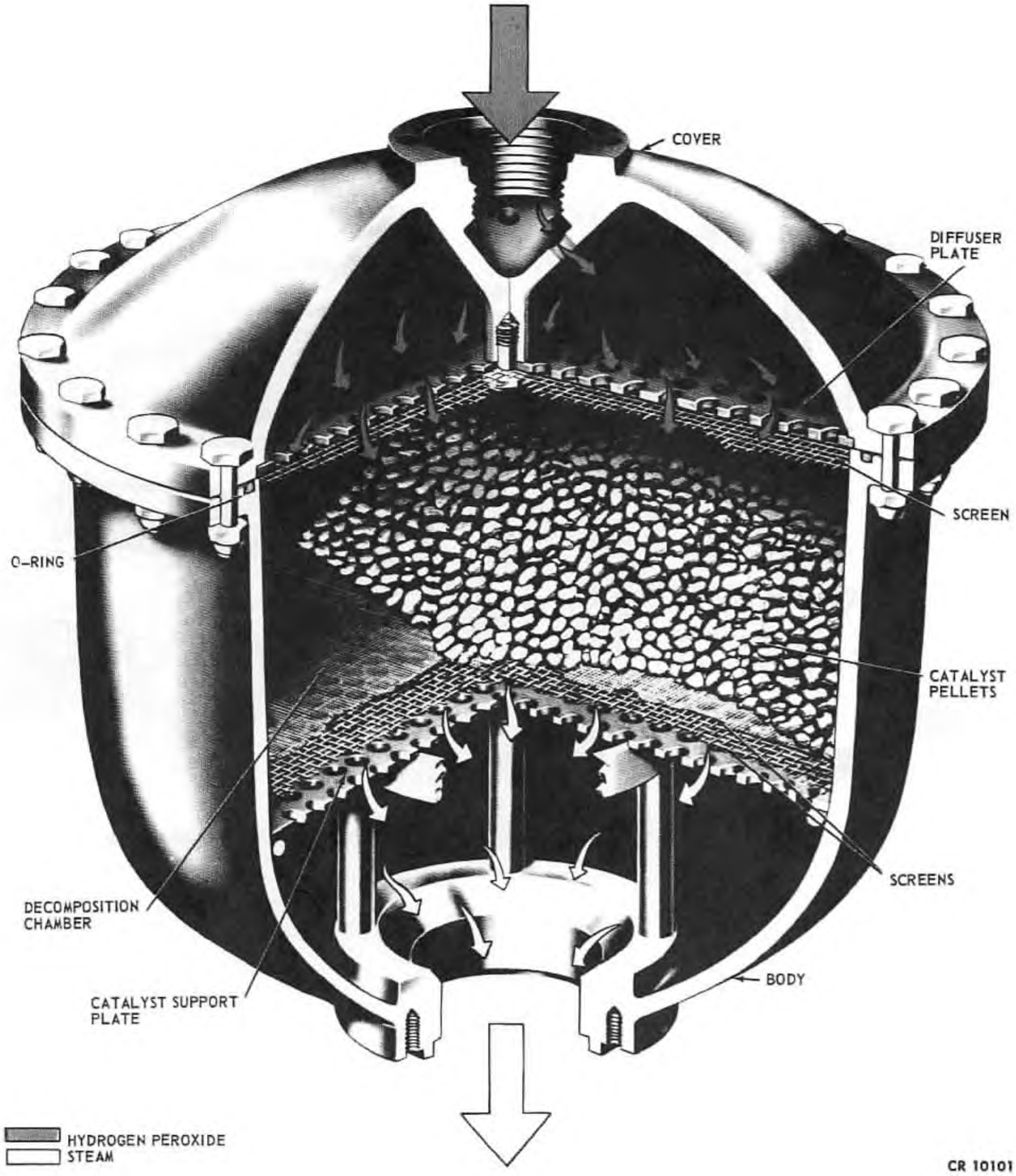

Figure VI-7 – Operation of the Steam Generator

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